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Title:	Active and passive meta-surfaces and their interaction with terahertz waves
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Active and passive meta-surfaces and their interaction with terahertz waves

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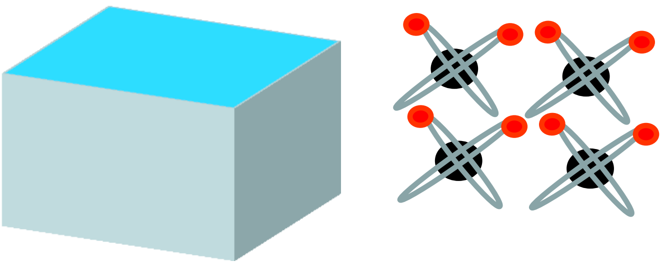
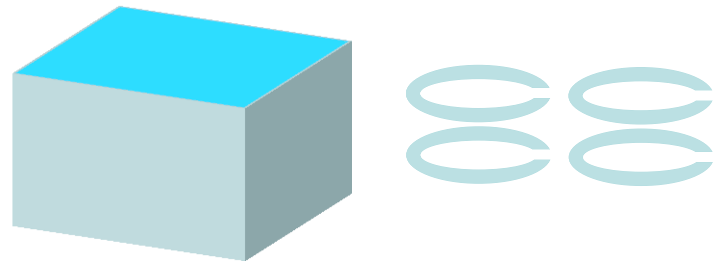
Outline

- **Introduction of metamaterials**
- **Why terahertz frequency?**
- **Passive THz metamaterial**
  - First realization of terahertz metamaterials
  - Understanding the inter-elemental coupling
- **Active terahertz metamaterial**
  - Optically tunable modulator
  - Electrically reconfigurable metamaterial
- **Ultrathin Terahertz polarization converter**
- **Future direction**

Metamaterials

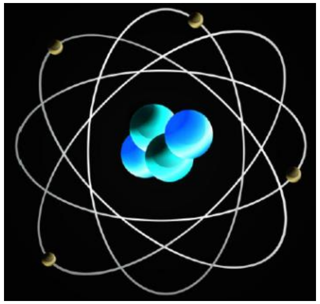
Metamaterials:

- Metamaterials represents the artificial or engineered materials that have properties beyond the natural materials

Natural Materials	Metamaterials
	
➢ Electromagnetic interaction depends on chemical composition of the materials	➢ Electromagnetic interaction depends on artificial resonators ➢ Provide unique capability to design material properties ➢ Scalable through wide range of EM spectrum

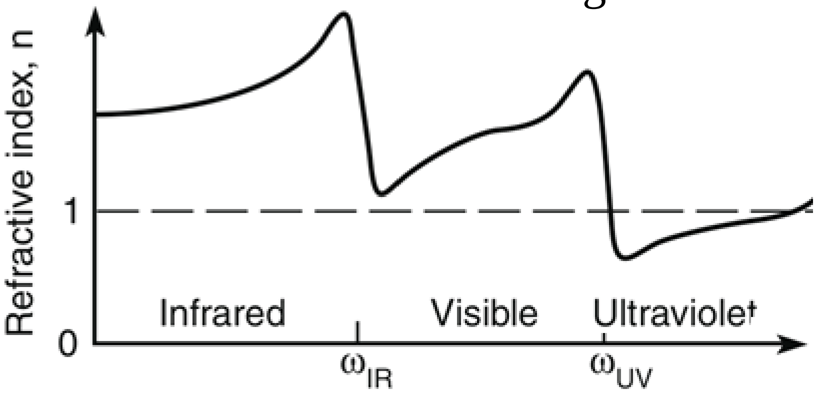
Pendry et al., Phys. Rev. Lett. 76, 4773 (1996), Pendry *et al.*, *IEEE Trans. Microwave Tech.* **47**, 2075 (1999)

Interaction of light with natural material



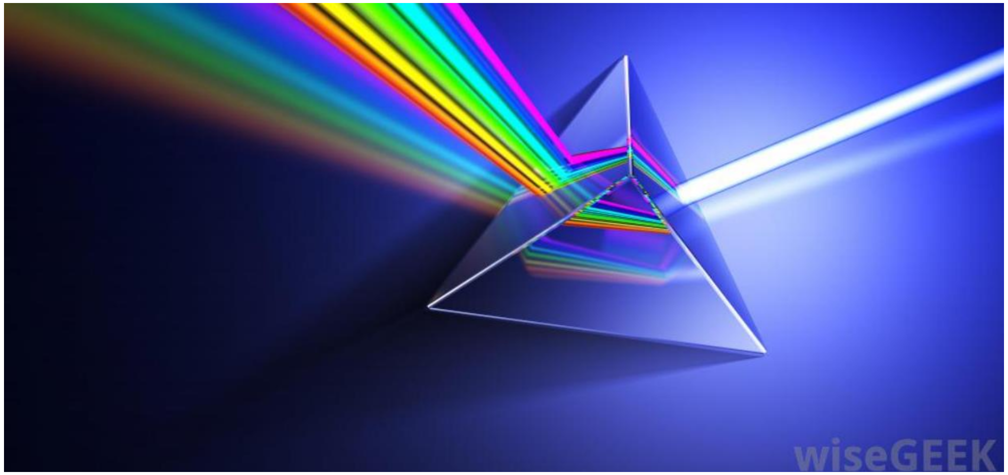
➢Electromagnetic interaction depends on chemical composition of the materials

Refractive index of glass

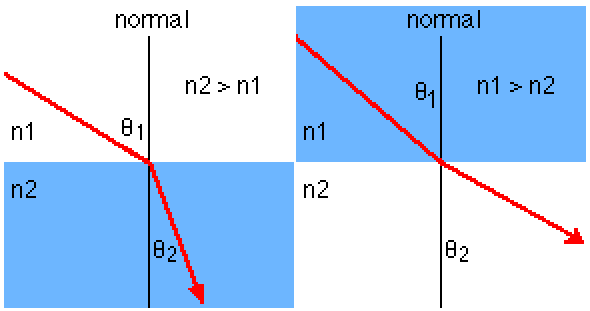


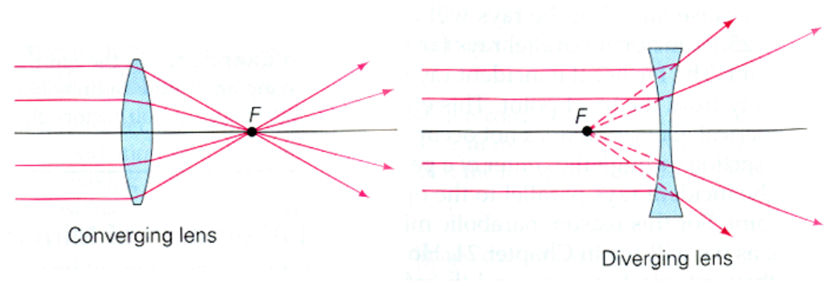
➢Resonance at UV – electronic transition

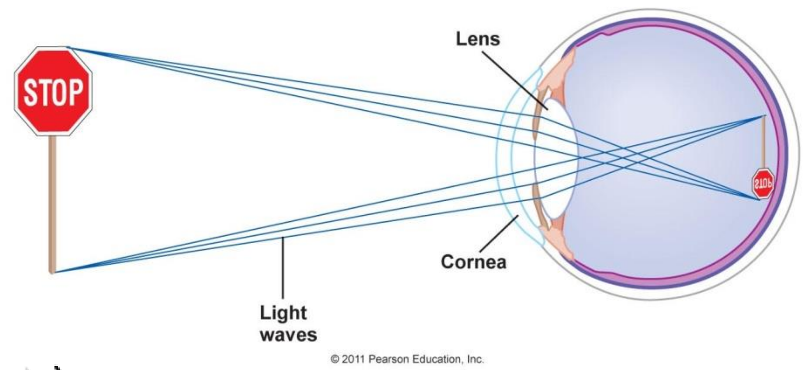
➢Resonance at IR – Si-O-Si bonds

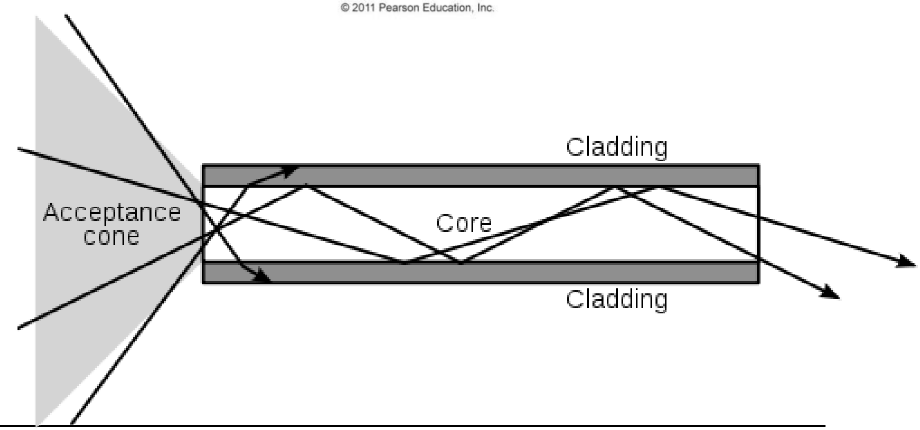


Refraction of light









Snell's Law:

$$n_1 \, Sin \, \theta_1 = n_2 \, Sin \, \theta_2$$

Willebrord Snell
(1580-1626)

Negative Index Materials

SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

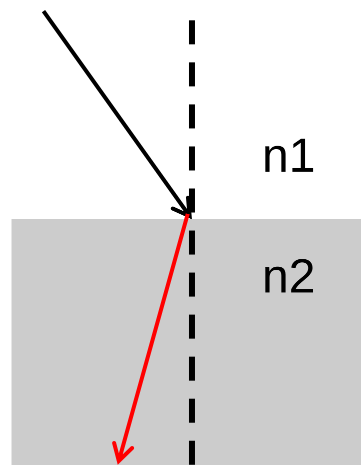
P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

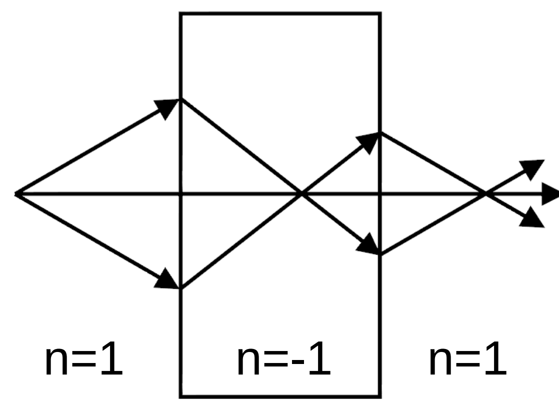
Usp. Fiz. Nauk 92, 517–526 (July, 1964)

- Light bends to the "wrong" direction, i.e. negative index of refraction
- Left-handed materials with opposite phase and group velocities
- Focusing with a flat slab, convex and concave lenses change places

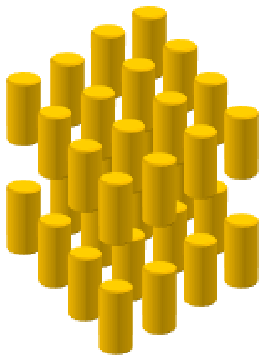
No natural material has been found to exhibit such properties !!

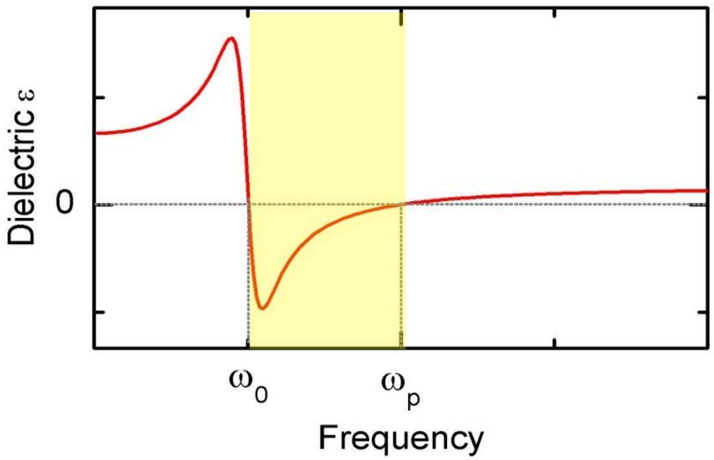
$$n = 1/\sqrt{\varepsilon\mu}$$



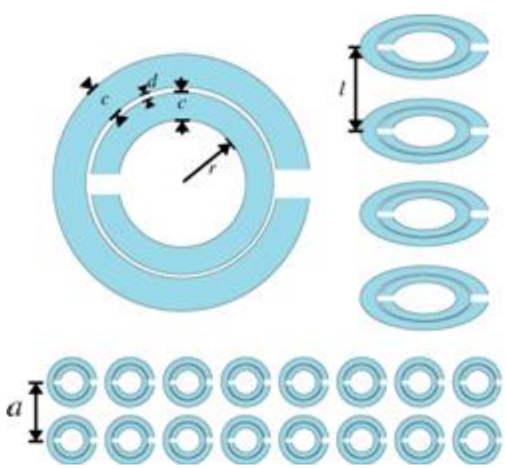


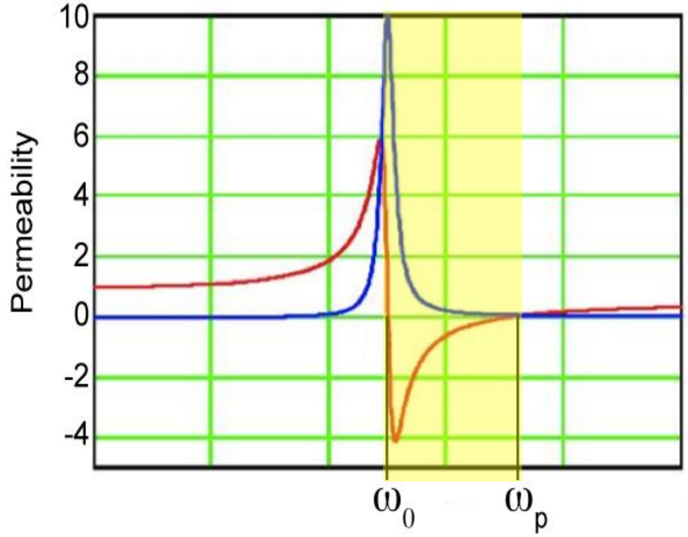
Controlling the Effective Electric and Magnetic Response





$$\varepsilon(\omega) = 1 - \frac{\omega_p^2 - \omega_0^2}{\omega^2 - \omega_0^2 + i\omega\Gamma}$$





$$\mu_{eff} = 1 - \frac{\dfrac{\pi r^2}{a^2}}{1 + \dfrac{2\sigma i}{\omega r \mu_0} - \dfrac{3}{\pi^2 \mu_0 \omega^2 C r^3}}$$

Pendry et al., Phys. Rev. Lett. 76, 4773 (1996), Pendry *et al.*, *IEEE Trans. Microwave Tech.* **47**, 2075 (1999)

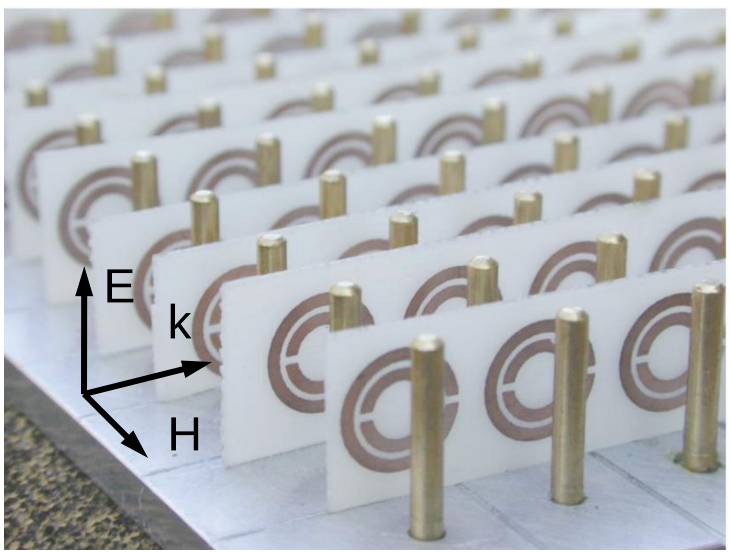
Simultaneously Negative ε and μ

VOLUME 84, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 2000

Composite Medium with Simultaneously Negative Permeability and Permittivity

D. R. Smith,* Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0319
(Received 2 December 1999)

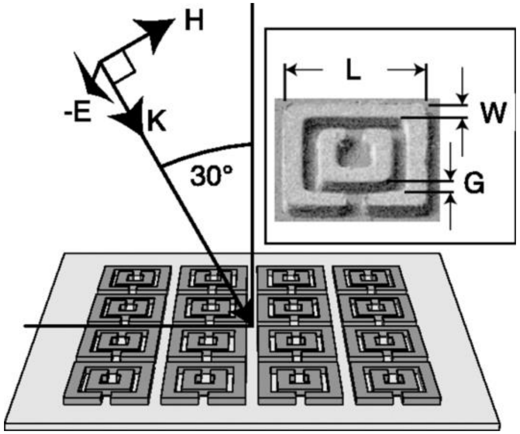
We demonstrate a composite medium, based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires, that exhibits a frequency region in the microwave regime with simultaneously negative values of effective permeability $\mu_{eff}(\omega)$ and permittivity $\varepsilon_{eff}(\omega)$. This structure

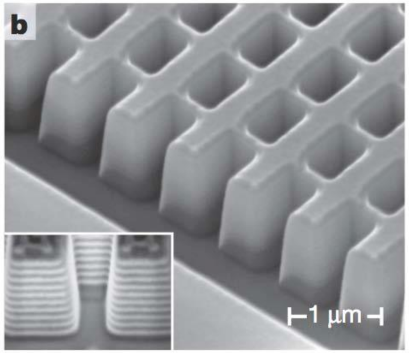


- Negative permittivity $\varepsilon < 0$ by metal rods array
- Negative permeability $\mu < 0$ by split-ring resonators array
- At certain frequency range with simultaneously negative $\varepsilon < 0$ and $\mu < 0$, microwave can propagate

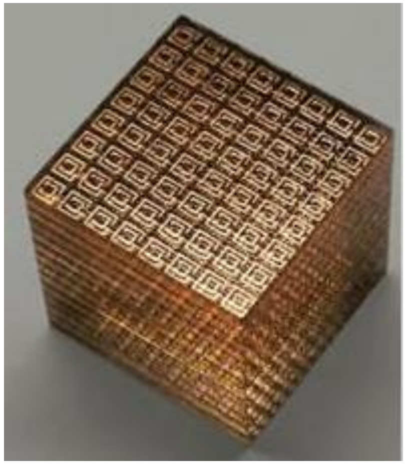
Electromagnetic Metamaterials

*Smith et al., PRL **84** (1999).*

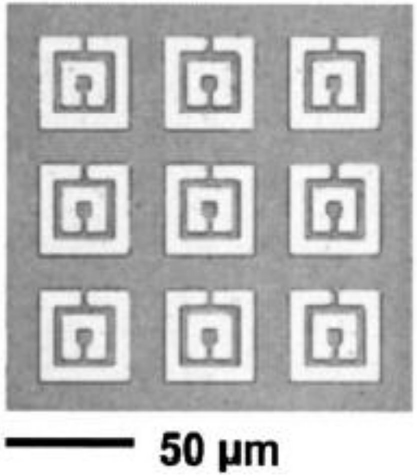


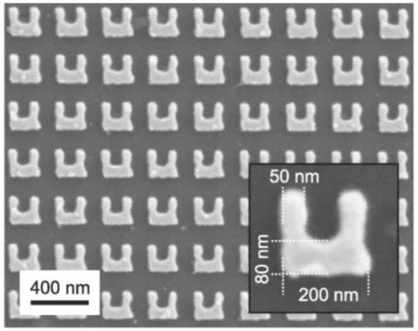


*Yen et al., Science **303**, 1494 (2004).*



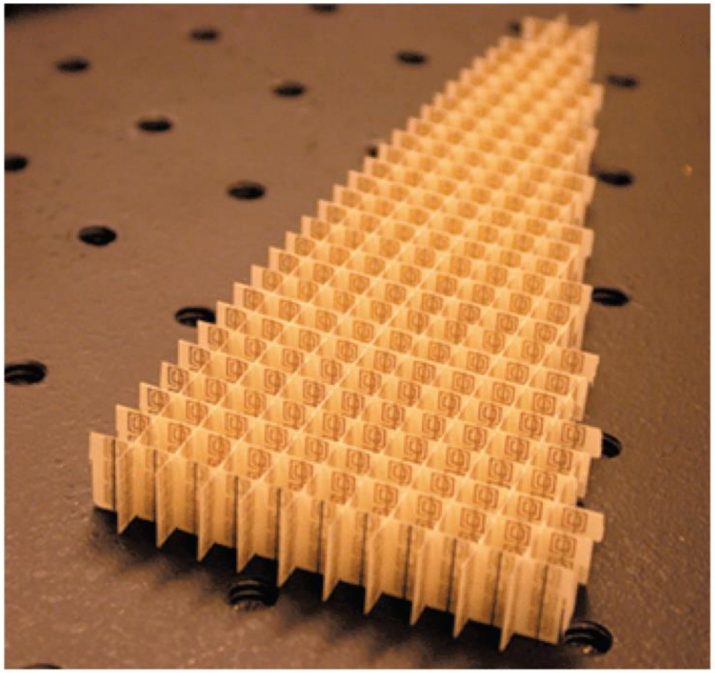
3D metamaterial



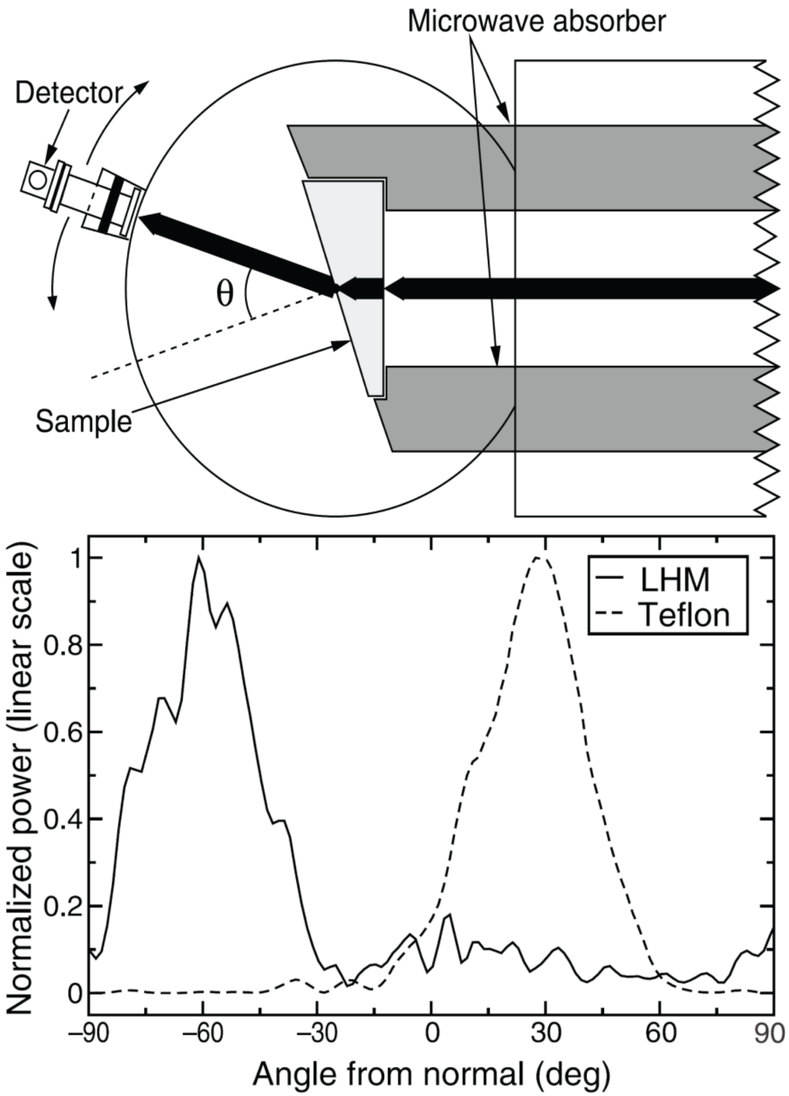


Azad *et al.*, *Opt. Lett.* **31**, 634 (2006)

Negative Refraction

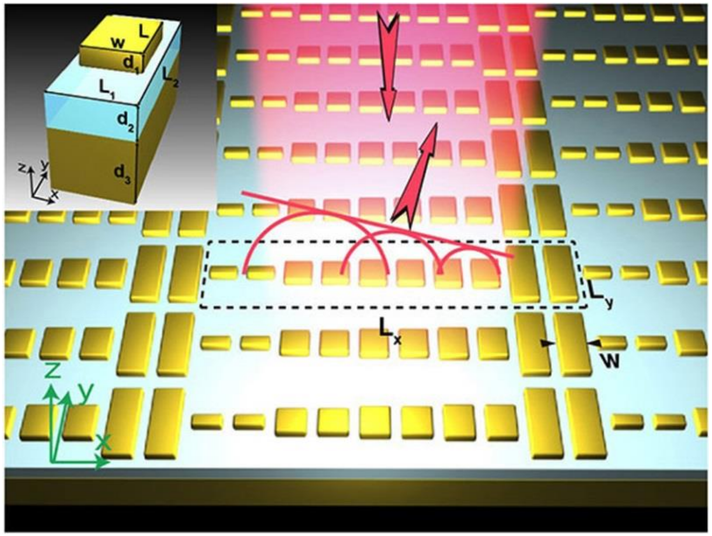


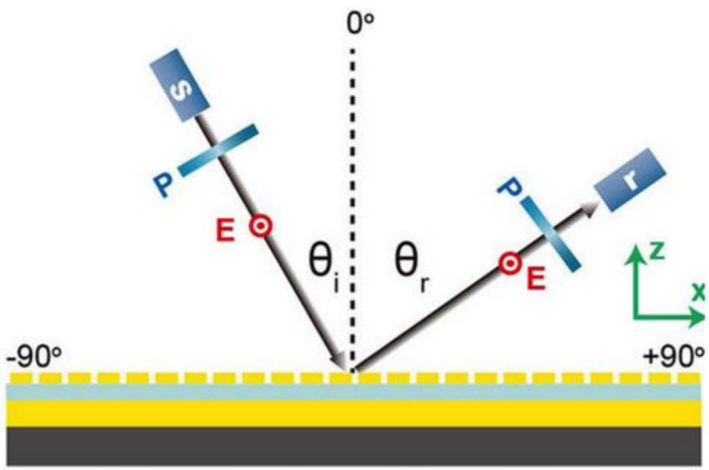
Shelby et al., Science ***292****, 77 (2001).*



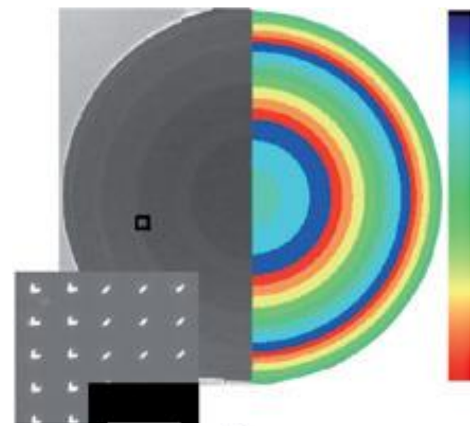
Meta-surface is future for flat integrated optics

Anomalous light refraction



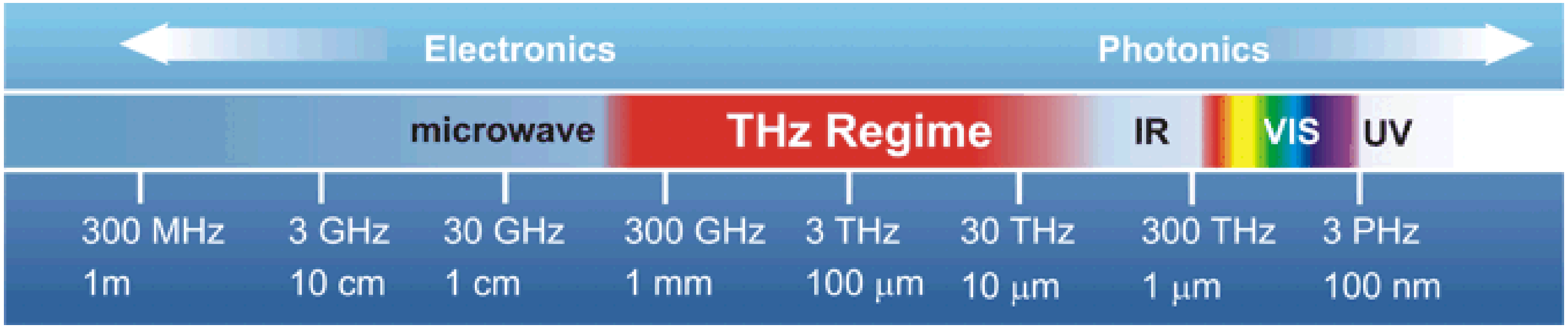


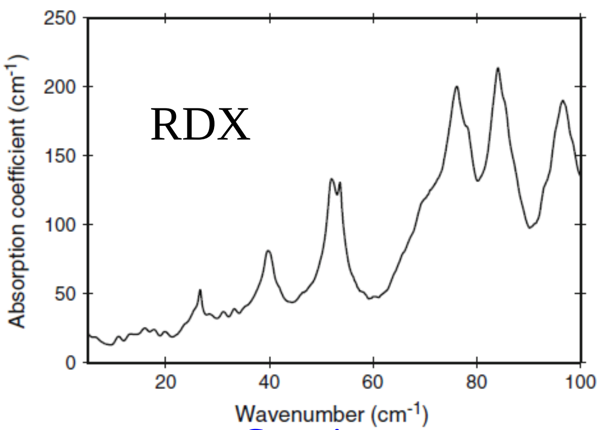
Focusing with a flat lens



N. Yu, NATURE MATERIALS, 13, 144 (2014)

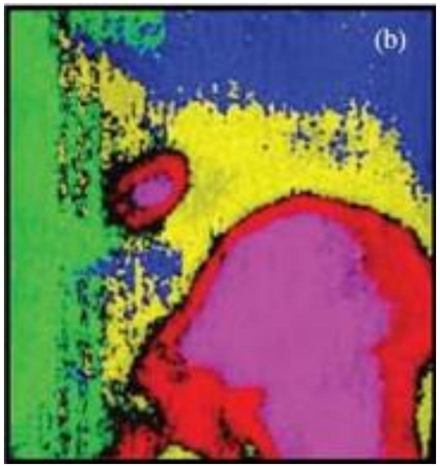
Why Terahertz?





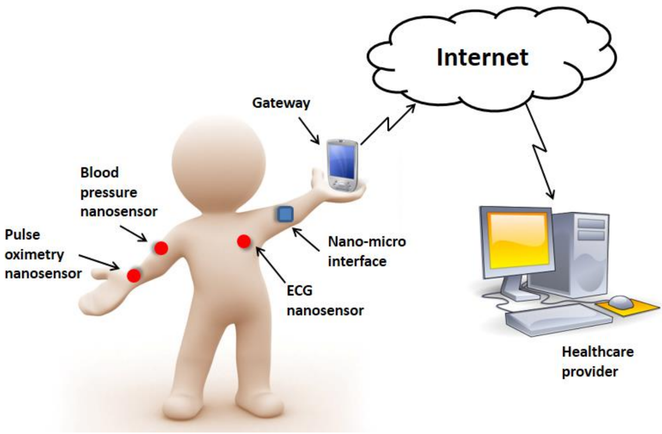
Sensing

V. Whitley, Anal. Bioanal Chem, 395, 315 (2009)



Imaging

Phys. Med. Biol. 55 4615 (2010)

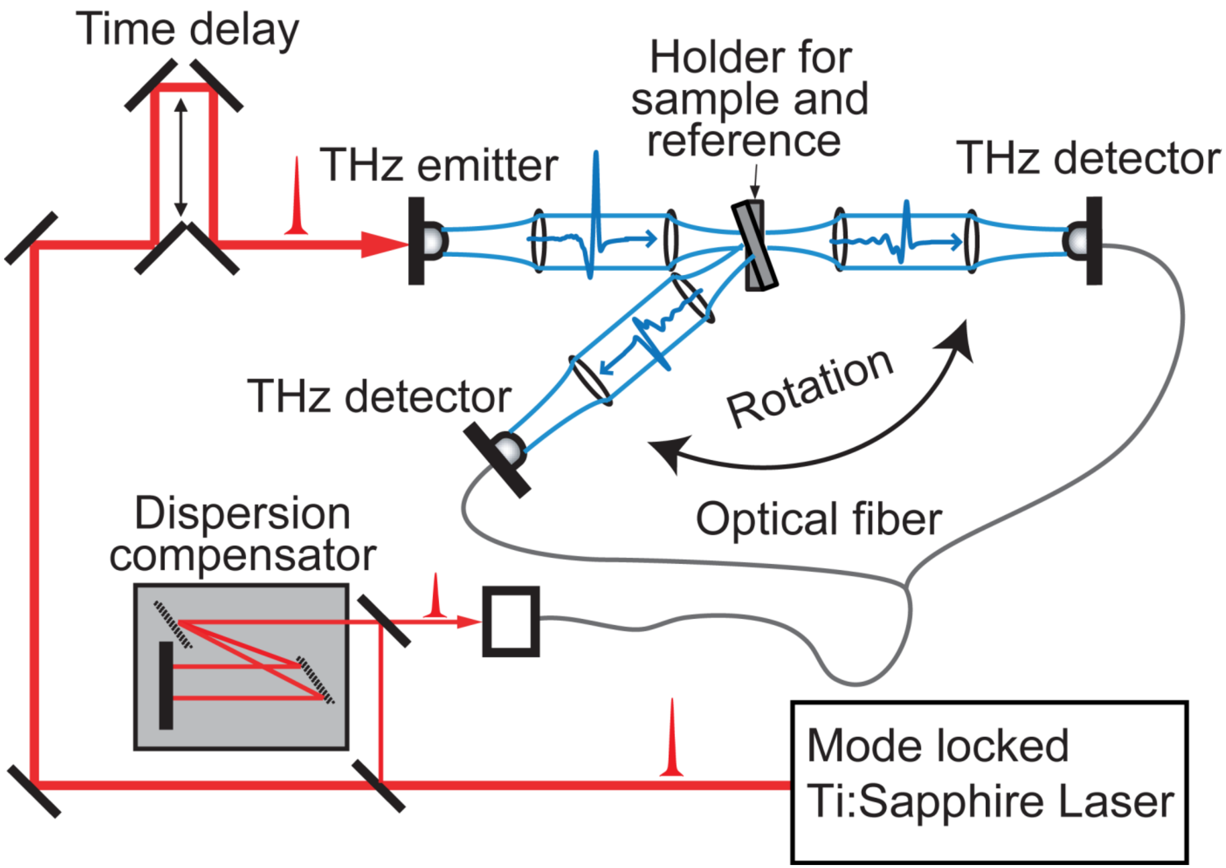


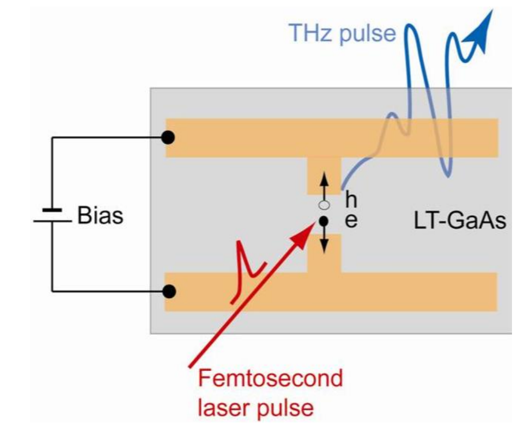
Communication

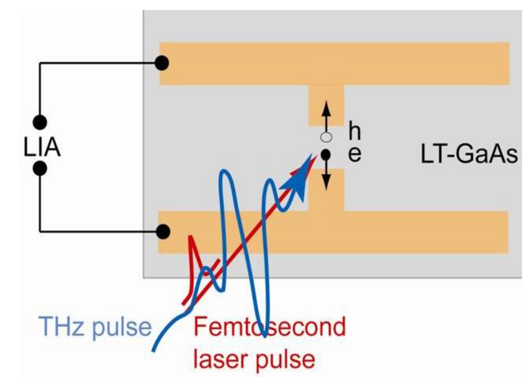
- <u>Extremely difficult generation/detection</u>
- <u>No practical terahertz devices</u>
- <u>THz Gap</u>

<u>Metamaterials are optimistic solutions !!</u>

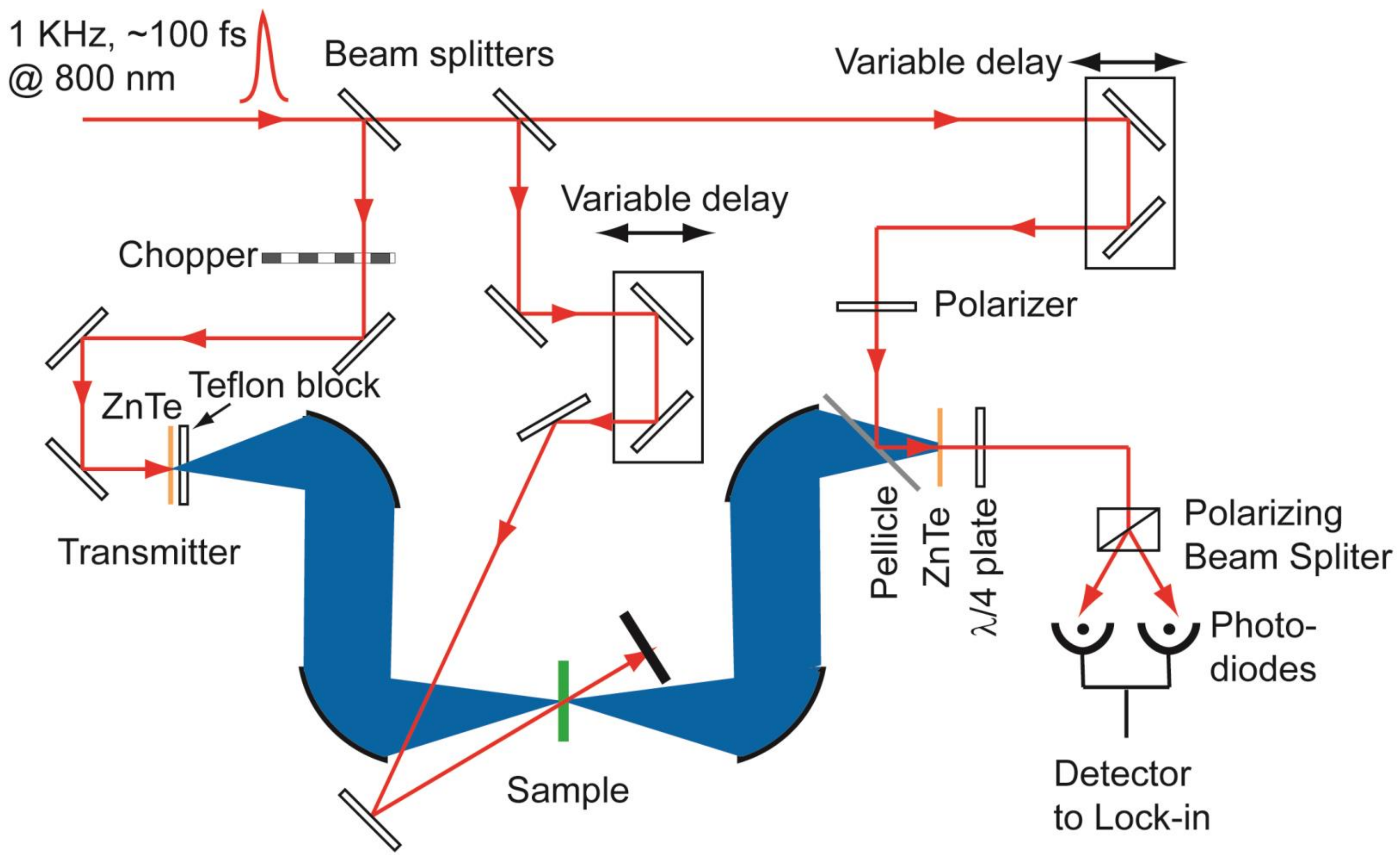
Optoelectronic (PC) Terahertz Spectrometer



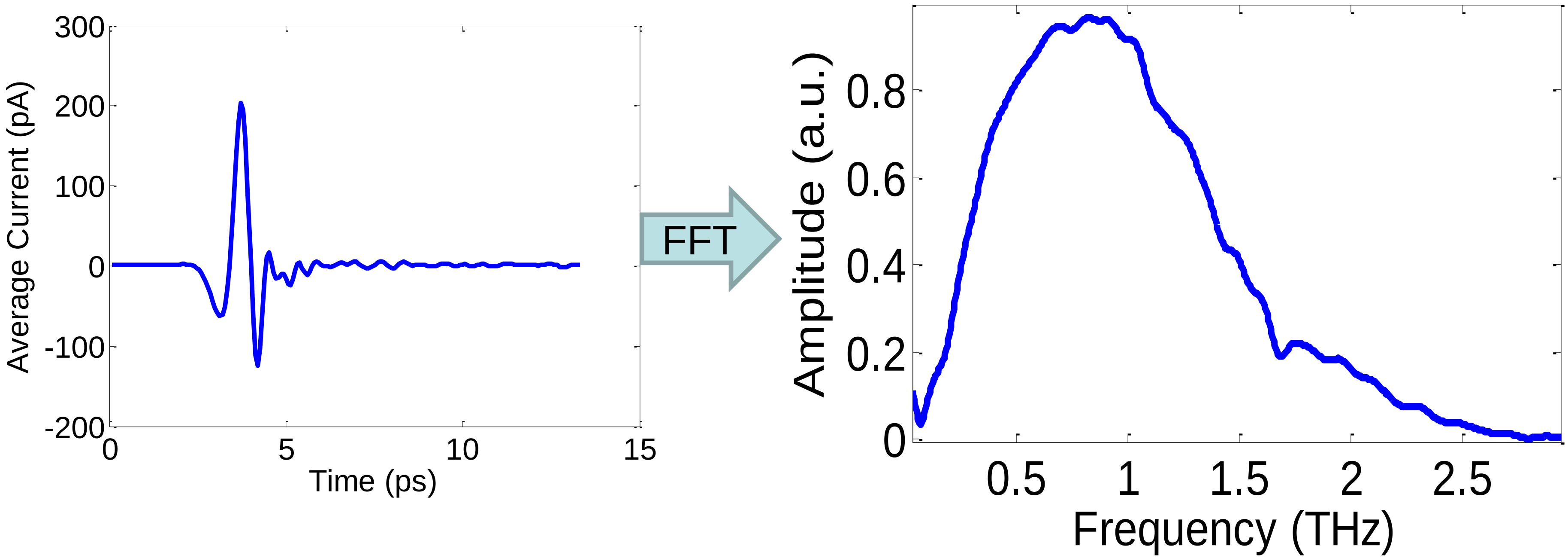




Optical THz Switch: Optical-Pump Terahertz-Probe



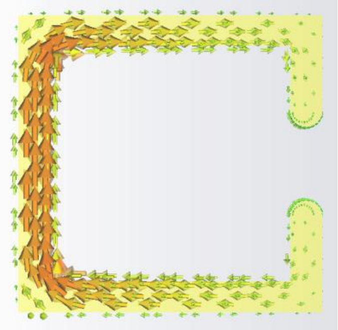
THz pulse to THz spectrum

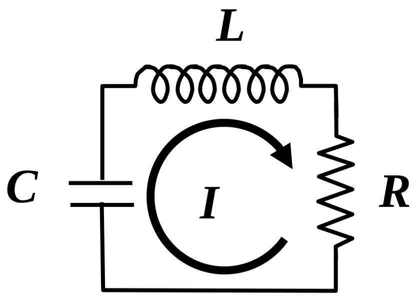


$$\left|\tilde{t}\right| = \left|E_S(\omega)/E_R(\omega)\right|$$

Metamaterial unit cell (SRR)

- size ~λ/10
- Collectively acts like an effective medium

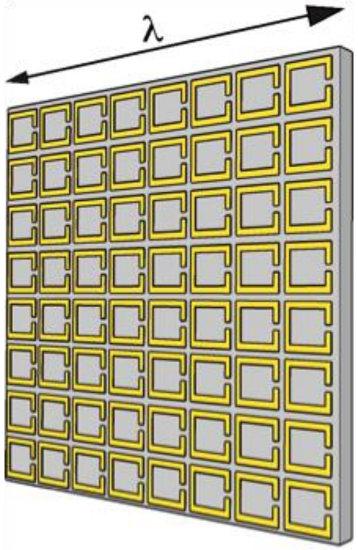




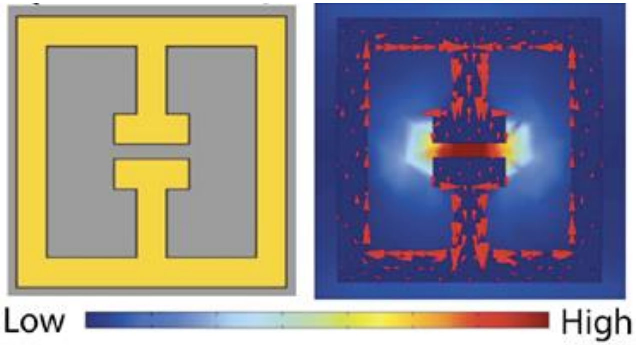
Equivalent circuit

$$\omega = \frac{1}{\sqrt{LC}}$$

Resonance frequency

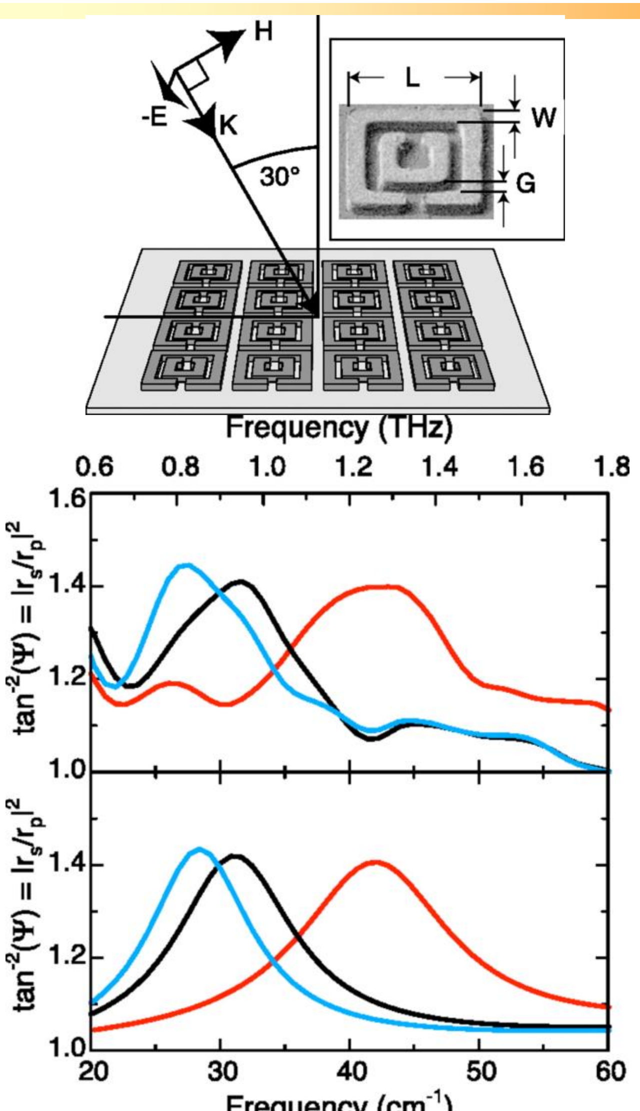


Array of SRR

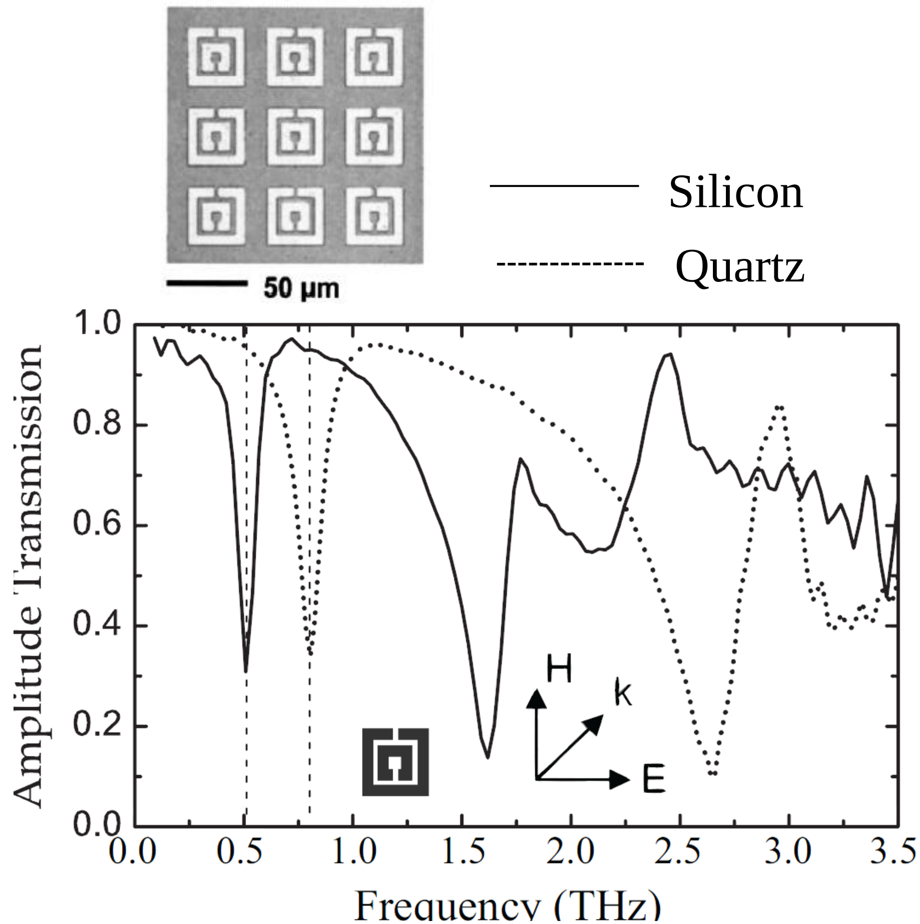


- Well disperse effective behavior dominated by individual resonance
- Effective behavior can be altered significantly from individual SRR by inter-elemental interaction

Realization of terahertz metamaterials



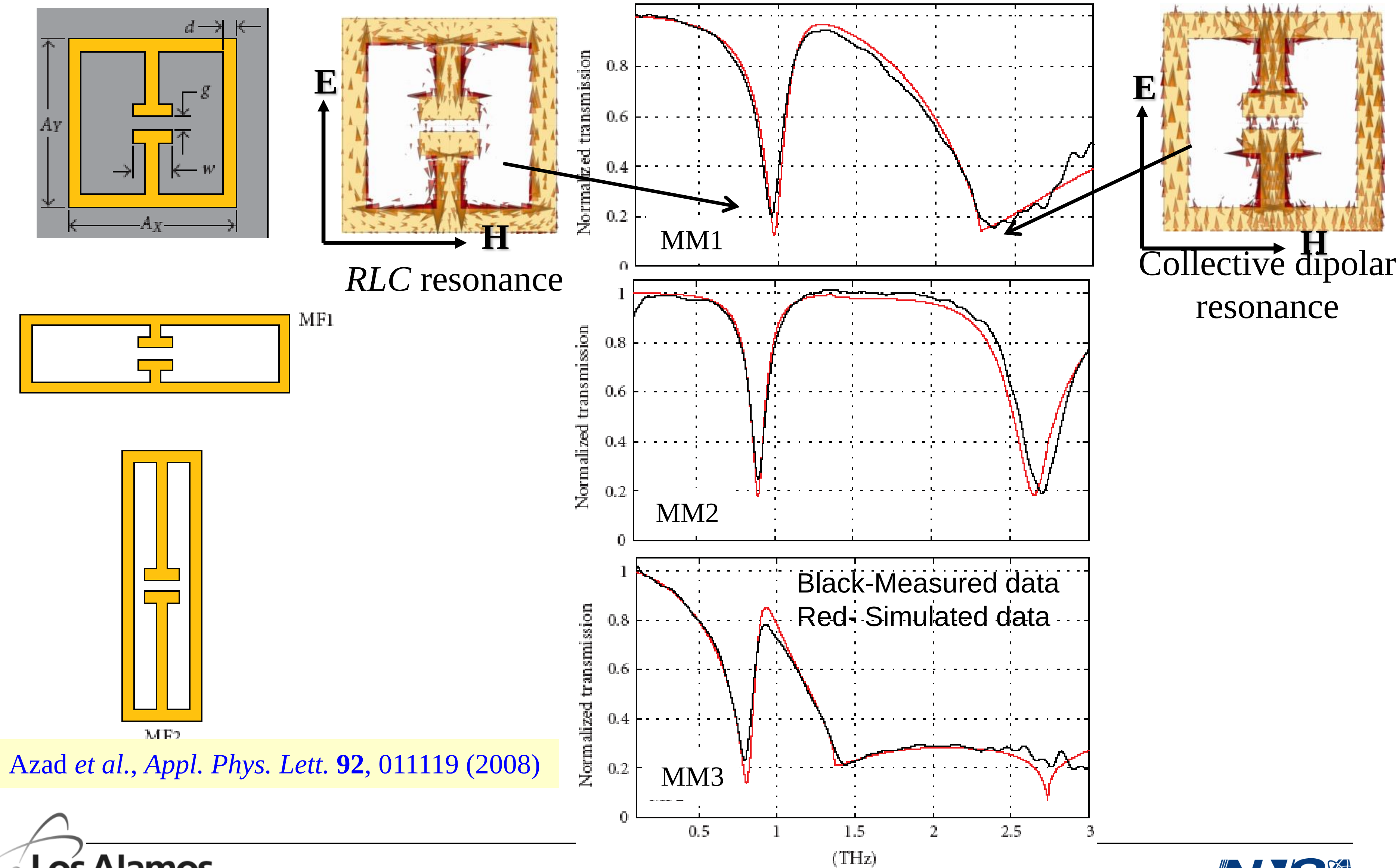
Yen et al., Science ***303****, 1494 (2004).*



$$\omega \propto 1/\sqrt{C} \quad \text{or} \quad \omega \propto 1/\varepsilon$$

Azad *et al., Opt. Lett.* **31**, 634 (2006)

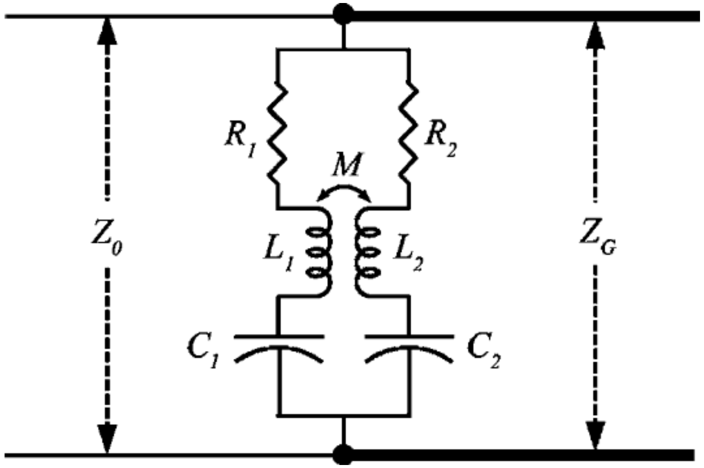
Resonances modes and intermodal interactions

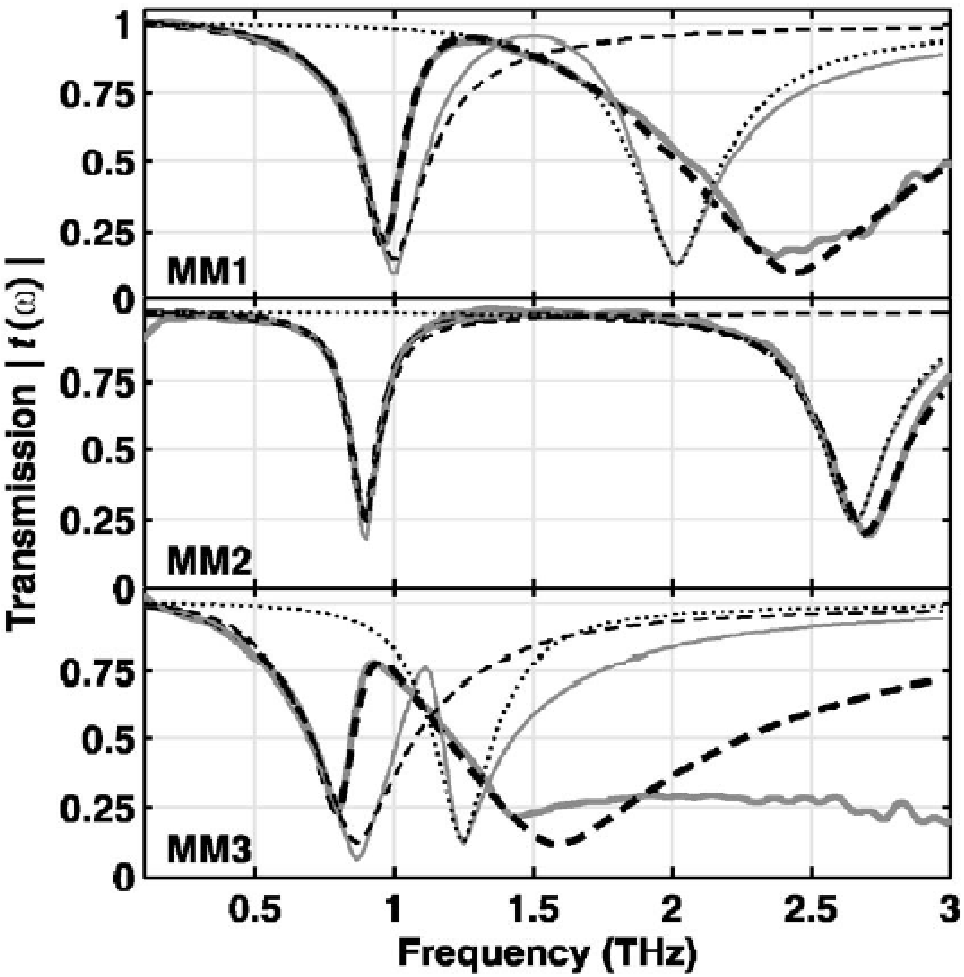


Azad *et al.*, *Appl. Phys. Lett.* **92**, 011119 (2008)

Coupling between eigen states

Transmission Line Model

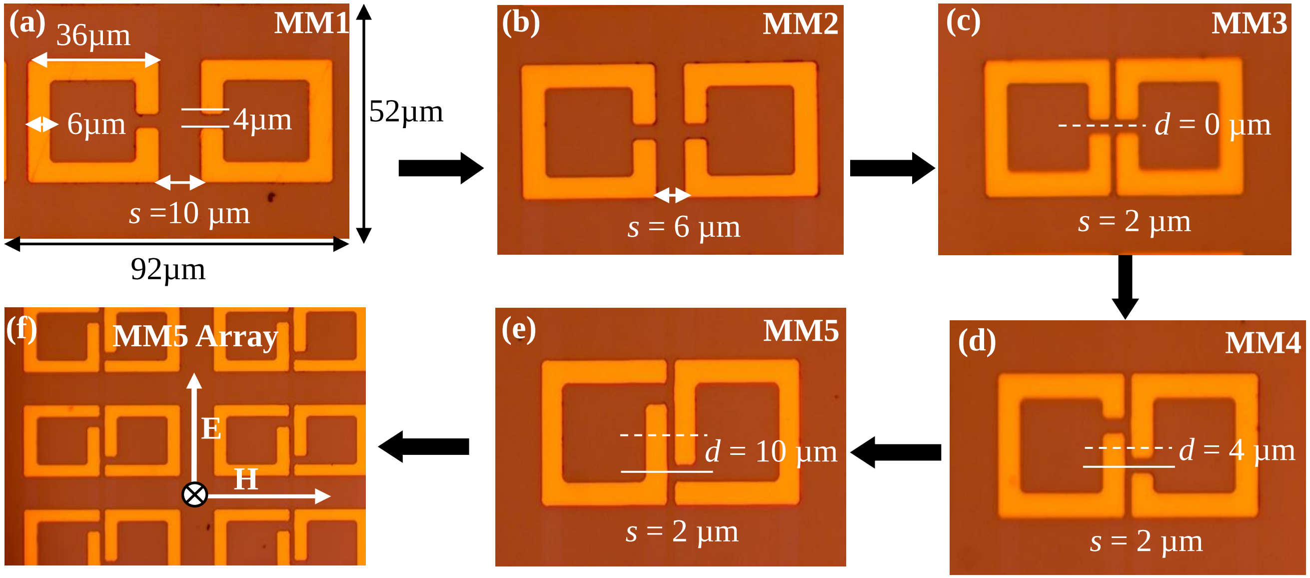




- ➢LC resonance interacts with dipolar resonance
- ➢L and C also varies with shape due to fringing fields

Azad *et al., Appl. Phys. Lett.* **92**, 011119 (2008)

Effect of Coulomb interaction in coupled MM

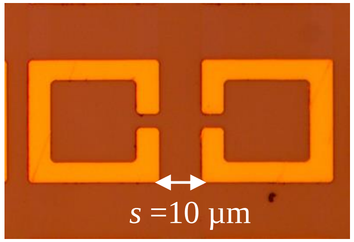


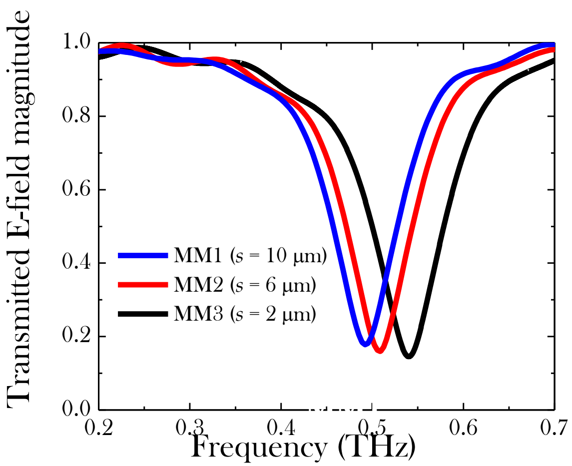
Vary separation *S*

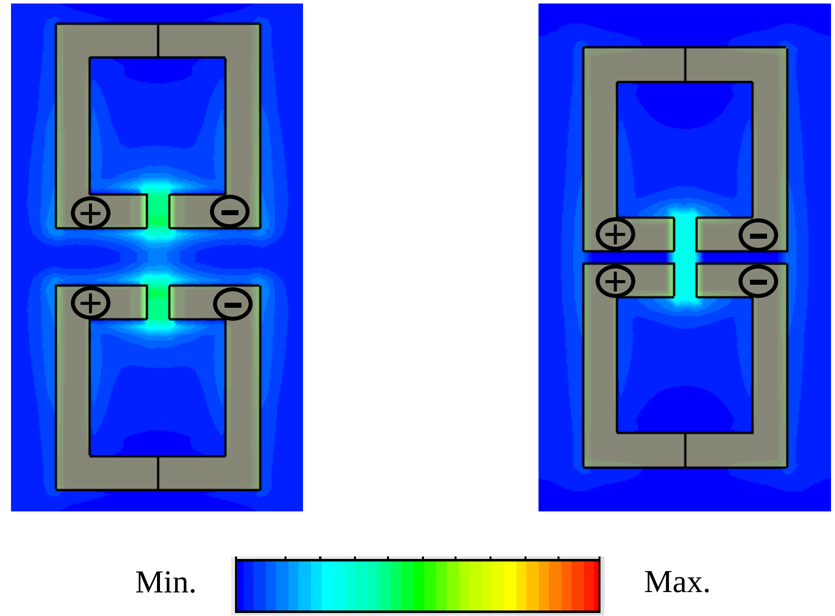
Vary gap asymmetry *d*

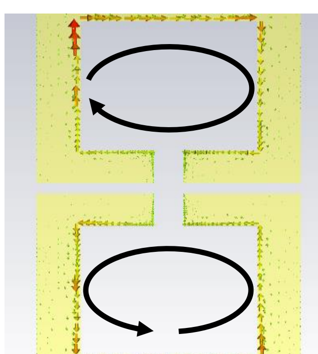
D. Roy Chowdhury et al. Opt. Exp. 19, 10679 (2011)

Effect of Coulomb interaction in coupled MM



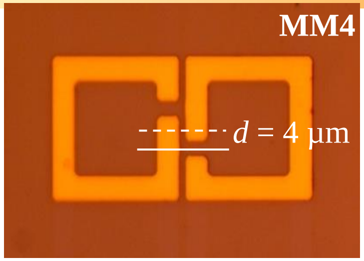


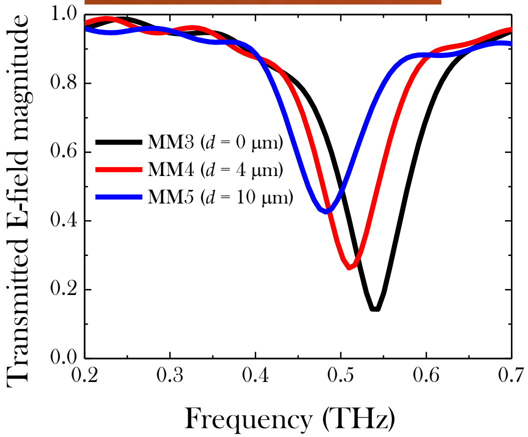


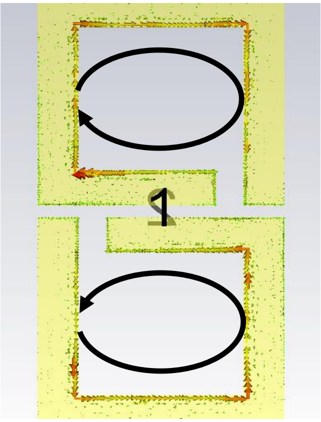


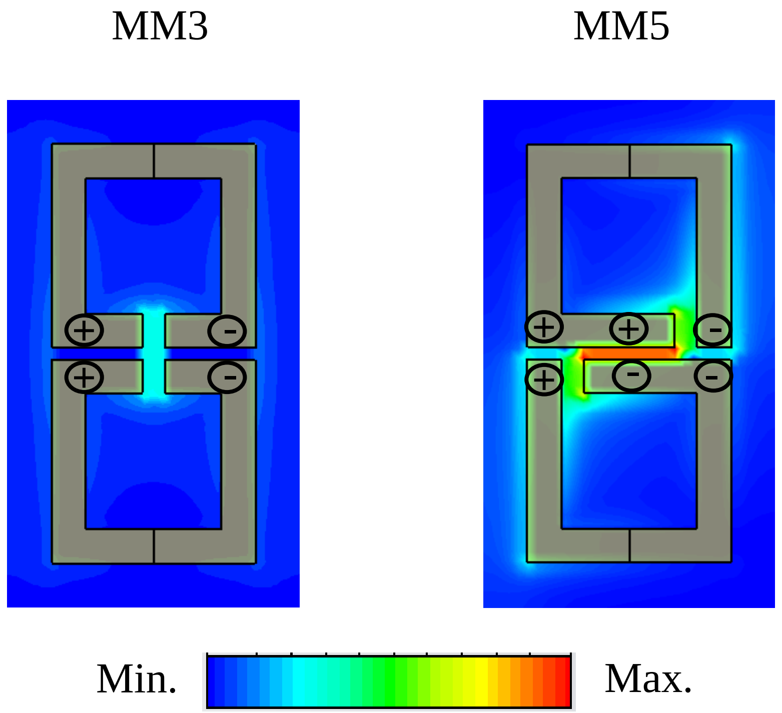
- Coulomb repulsion of similar charges leads to resonance blue shift

Effect of Coulomb interaction in coupled MM



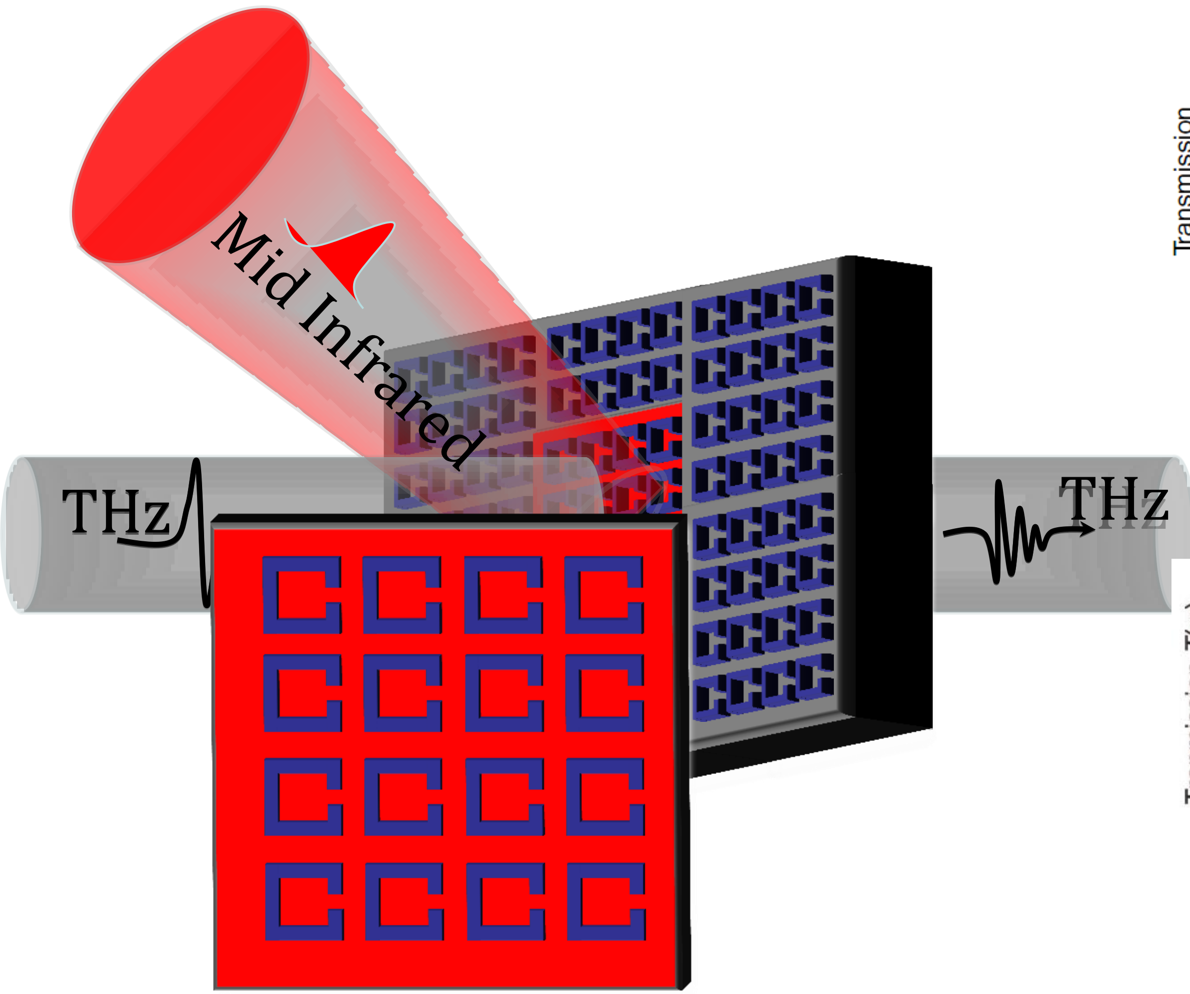


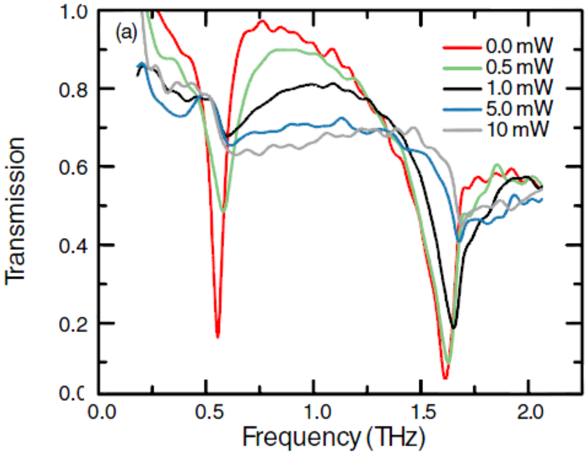




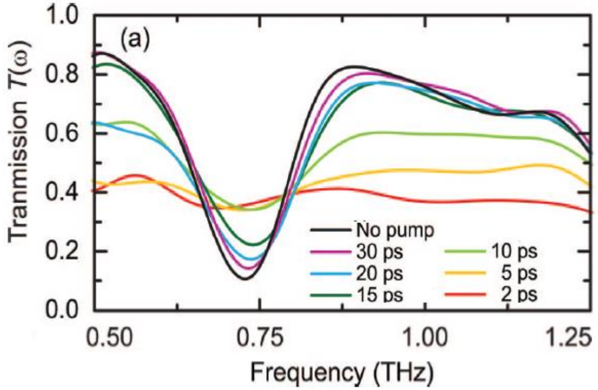
- Coulomb attraction of opposite charges leads to resonance red shift
- Electric field enhancement in between the SRRs

Optical switching using bulk semiconductor substrates



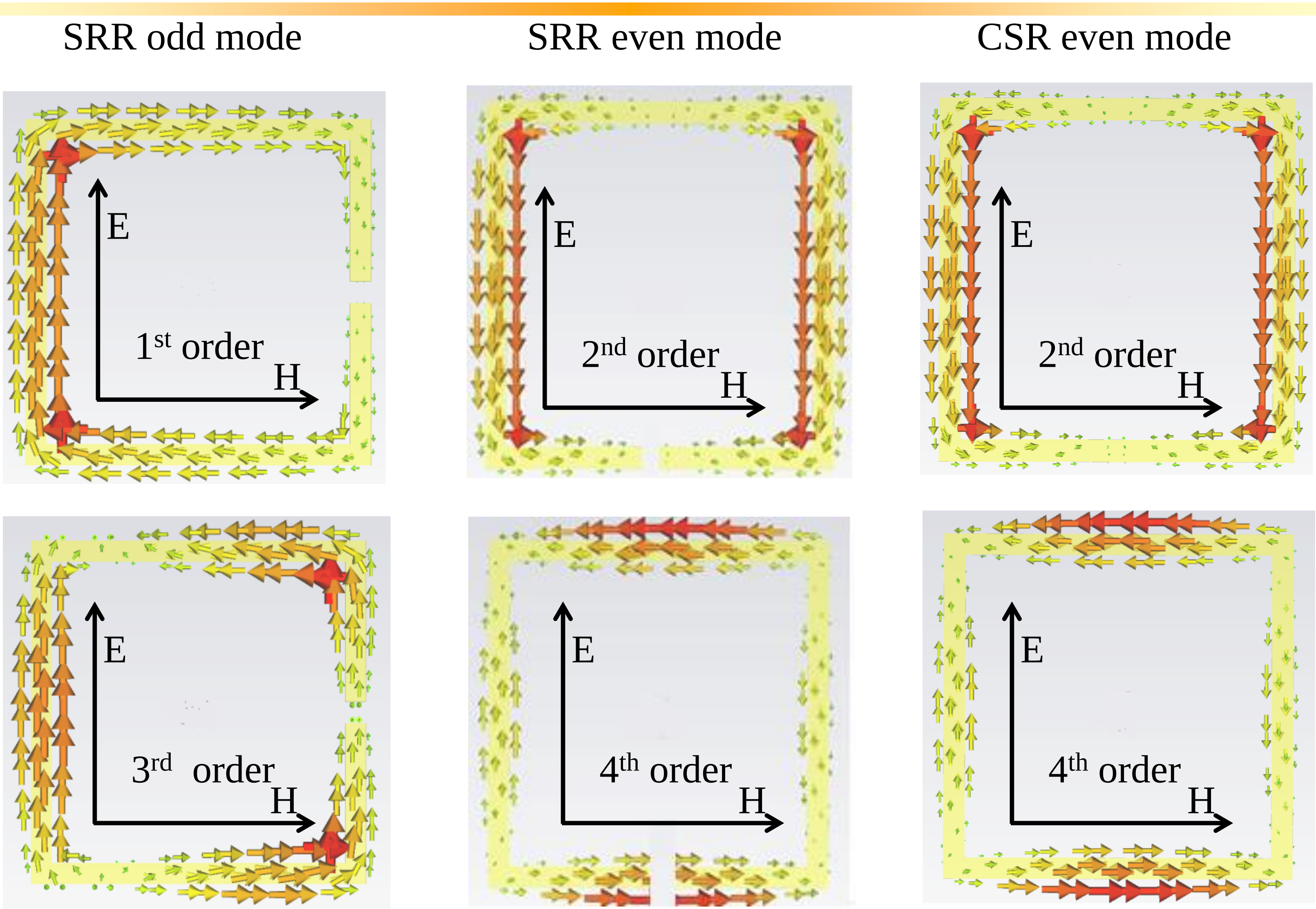


W. Padilla, PRL ***96, 107401 (2006)***



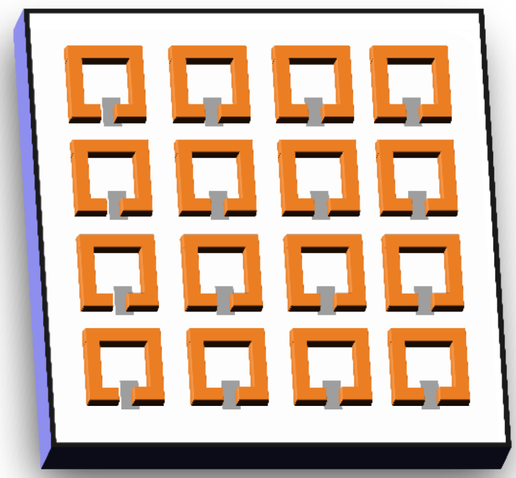
H. Chen, OPTICS LETTERS ***32****, 1620 (2007)*

Excitation of odd or even resonances in SRR

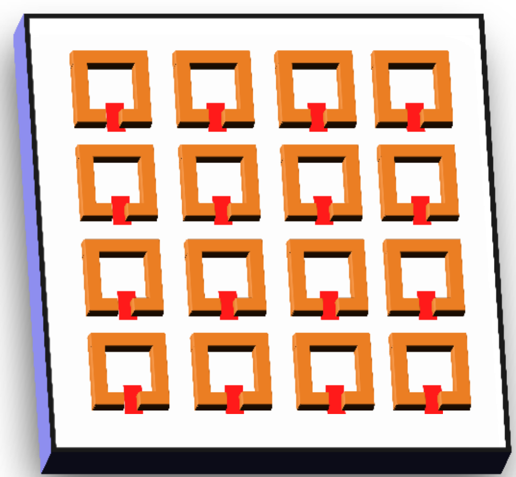


Optically reconfigurable metasurface

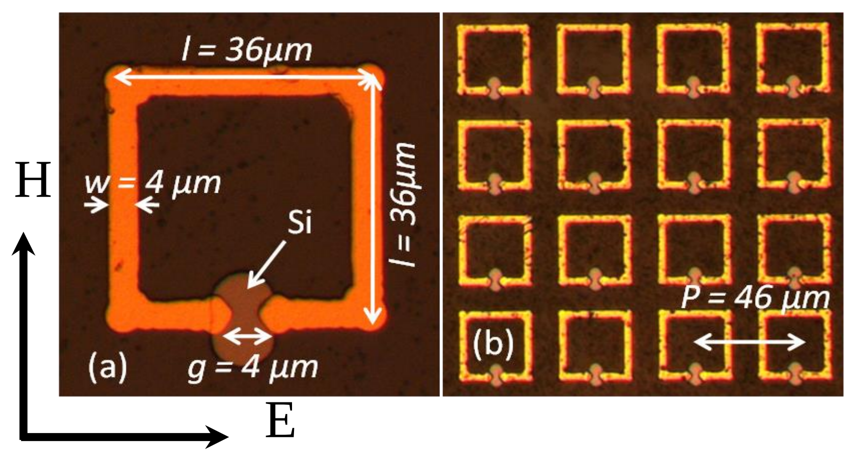
Sample before photoexcitation



Si island becomes conductive



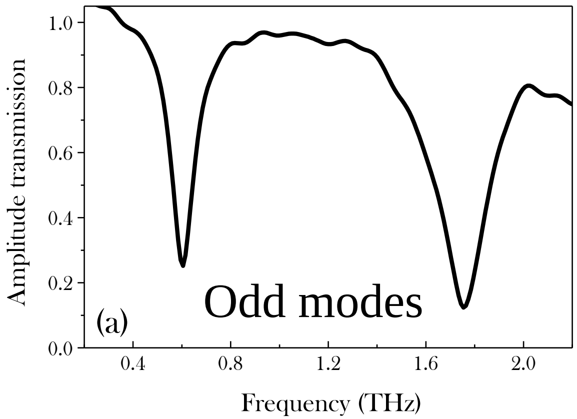
- Substrate is 0.5 micron thick silicon film on sapphire substrate (SOS)
- Silicon islands are small and have unnoticeable effect on THz transmission while not integrated with SRR.
- Photo excitation transforms the SRR to a CRR, therefore, change the resonant conditions.
- Excites only the even mode resonances



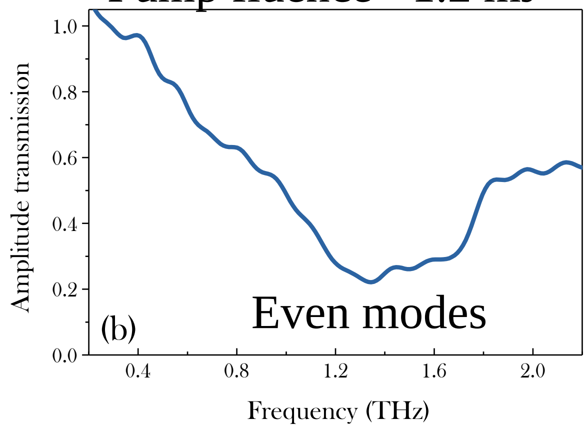
D. Chowdhury, et. al. Appl. Phys. Lett. 99, 231101 (2011)

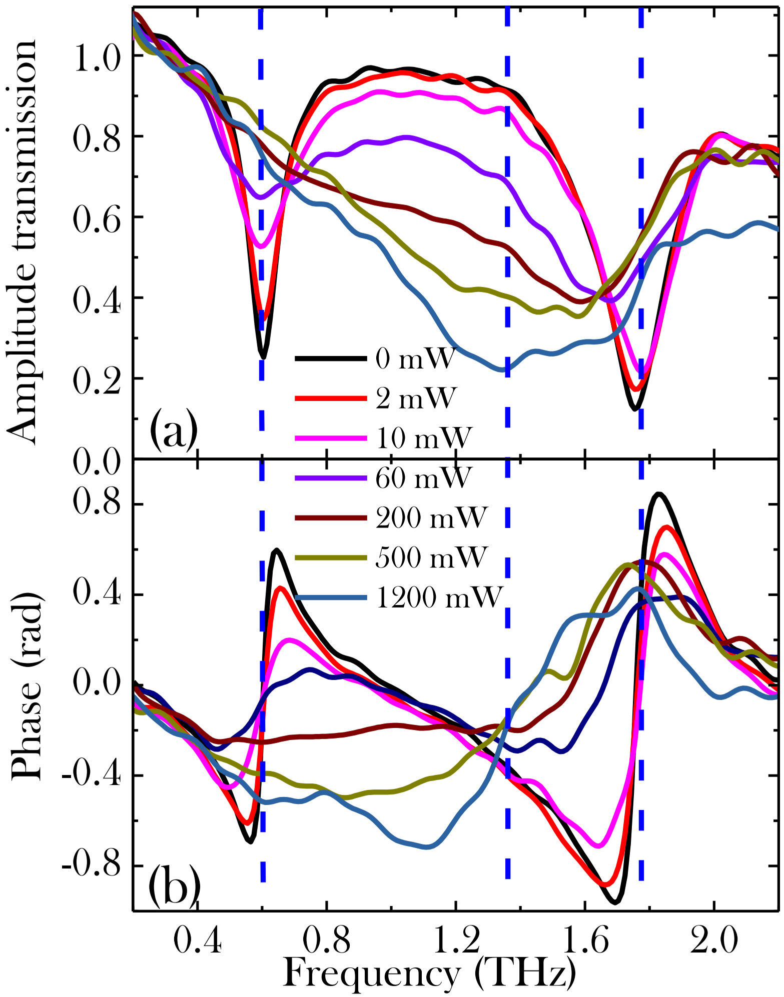
Amplitude and phase modulation with optical excitation

w/o optical excitation

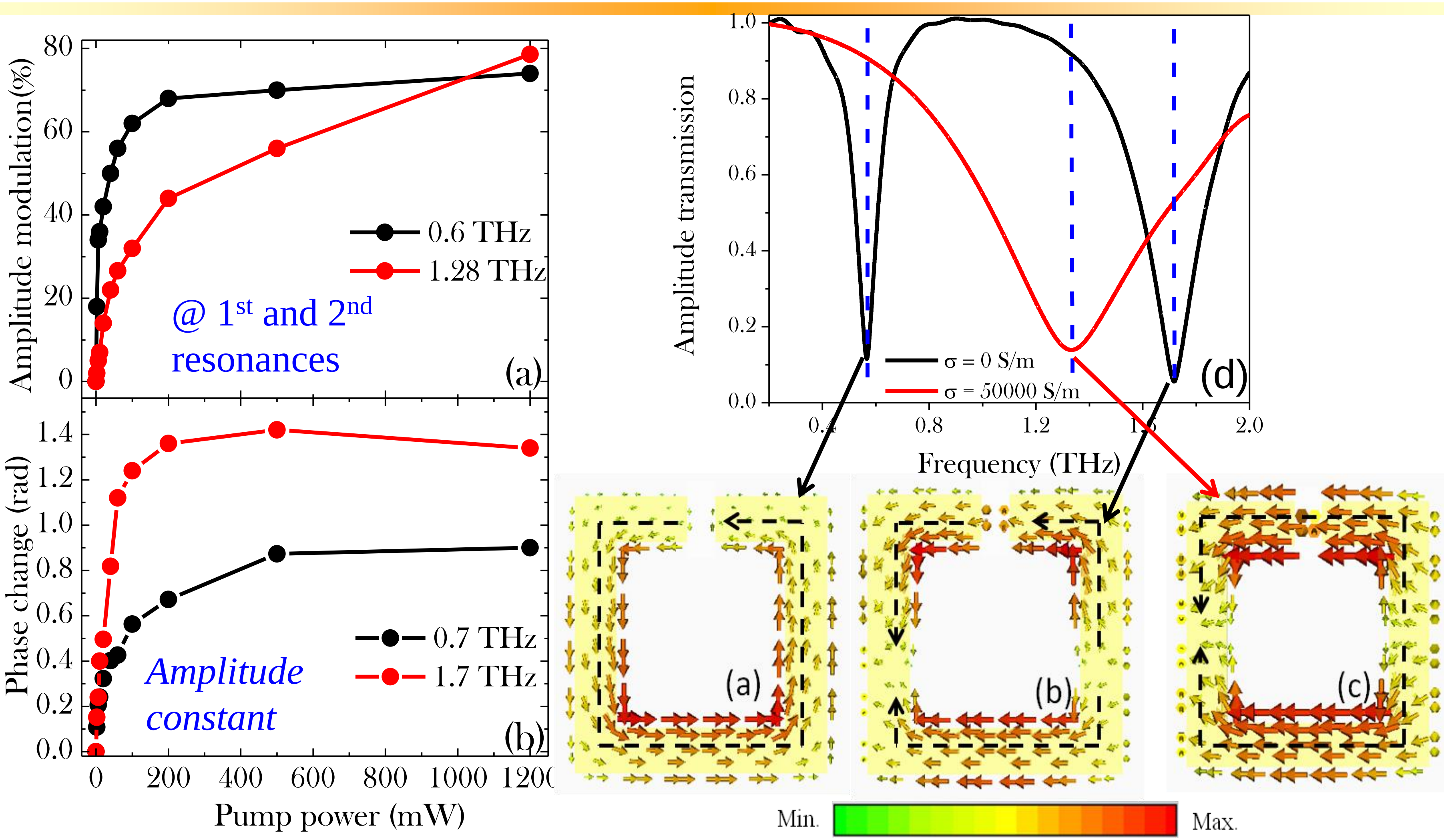


With optical excitation
Pump fluence =1.2 mJ

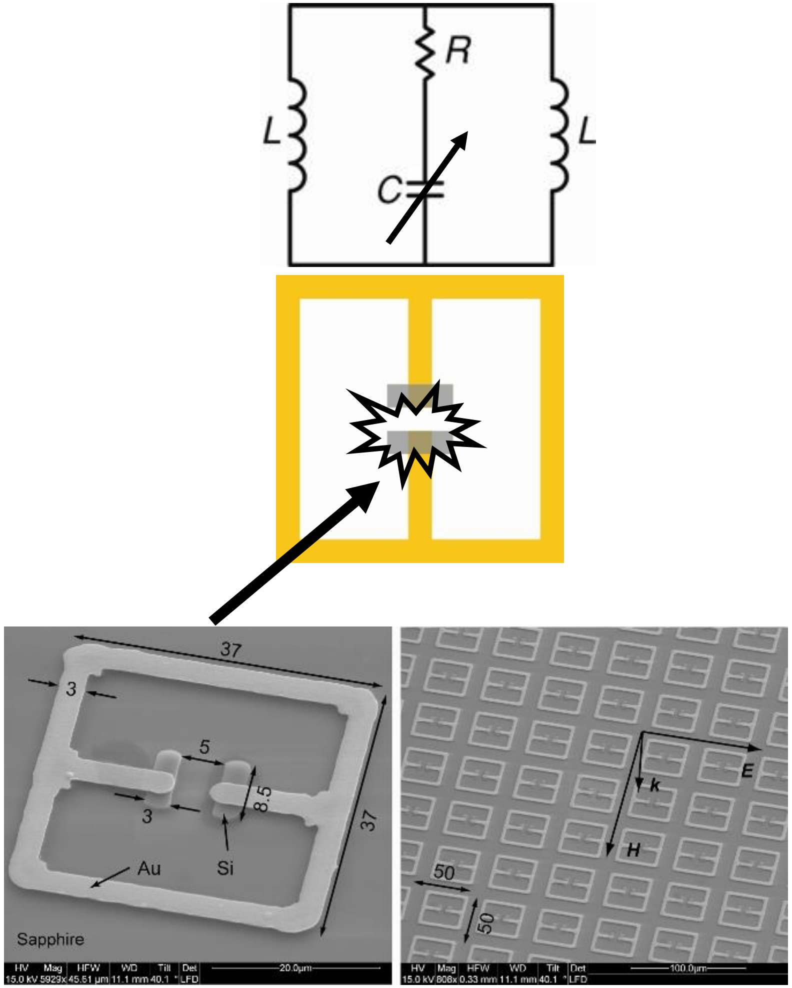


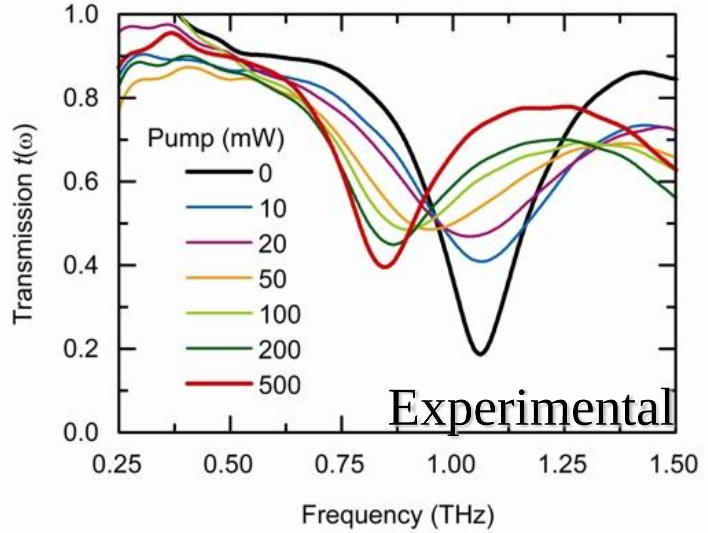


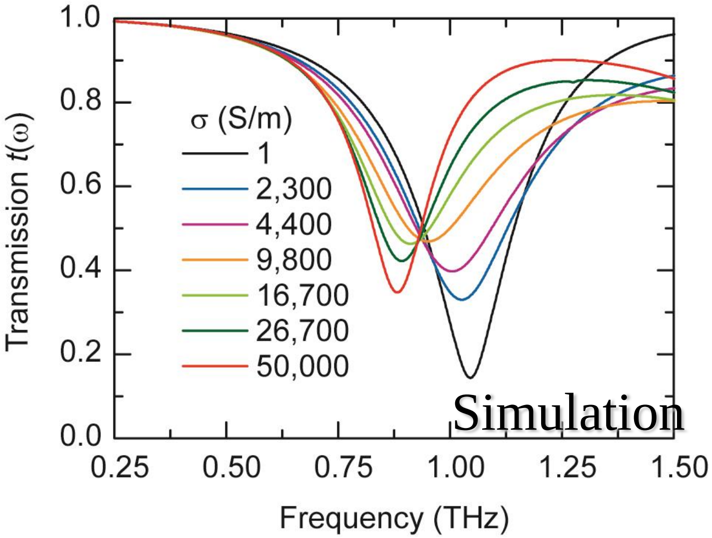
Amplitude and phase modulations due to optical excitation



Optically controlled frequency modulation

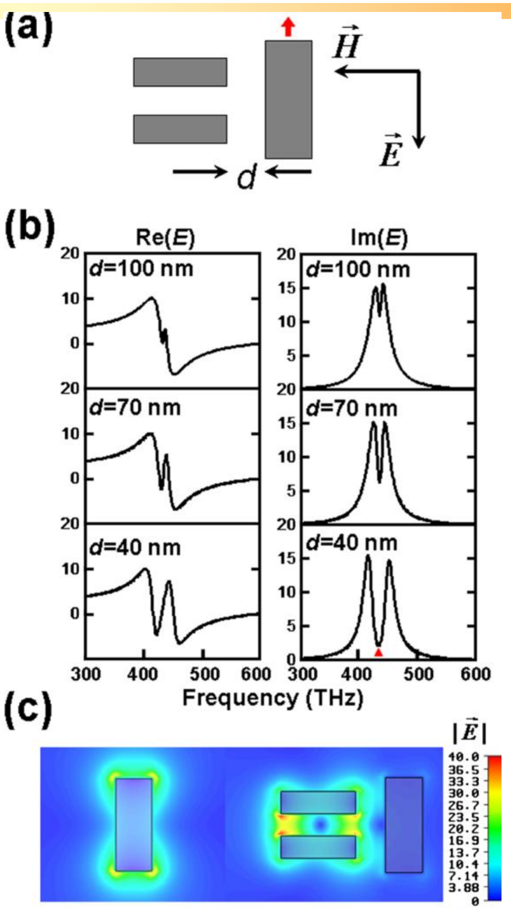






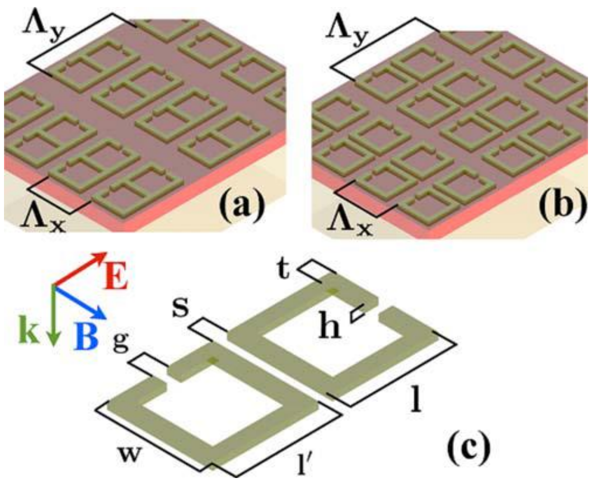
Chen *et al.*, *Nature Photon.* **2**, 295 (2008).

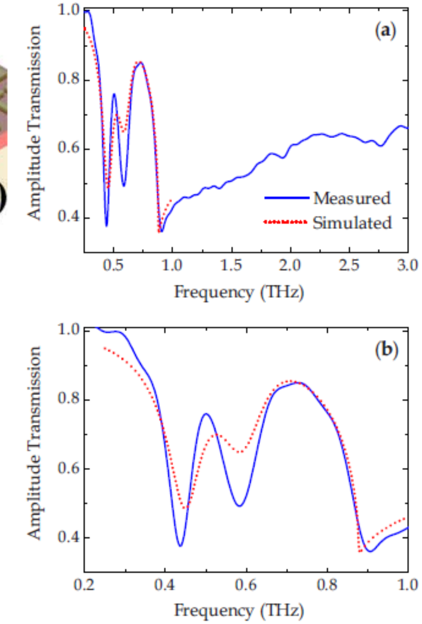
Static manipulation of coupling between resonators



S Zhang et al.
Phys. Rev. Lett., 101, 047401 (2008)

- ➢ Plasmonic coupling between bright and dark resonance modes

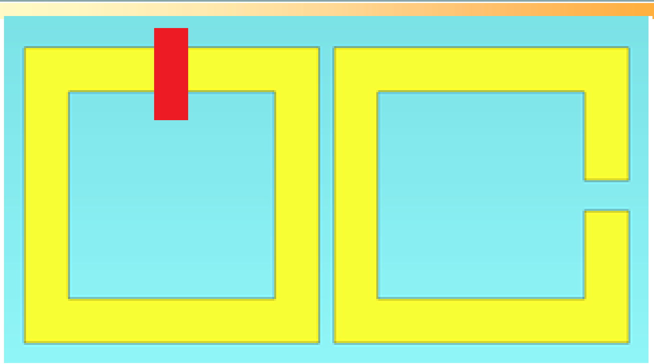




R. Singh et al., Phys. Rev. B 79, 085111 (2009)

- ➢ Electromagnetic coupling in Metamaterials
- ➢ Analogue of electromagnetically induced transparency
- ➢ Slow light

Design of the unit metamolecule



Dark Bright

Conditions for strong coupling:

- $\omega_{0(Bright)} \approx \omega_{0(Dark)}$
- Separation between Bright and Dark elements must be small

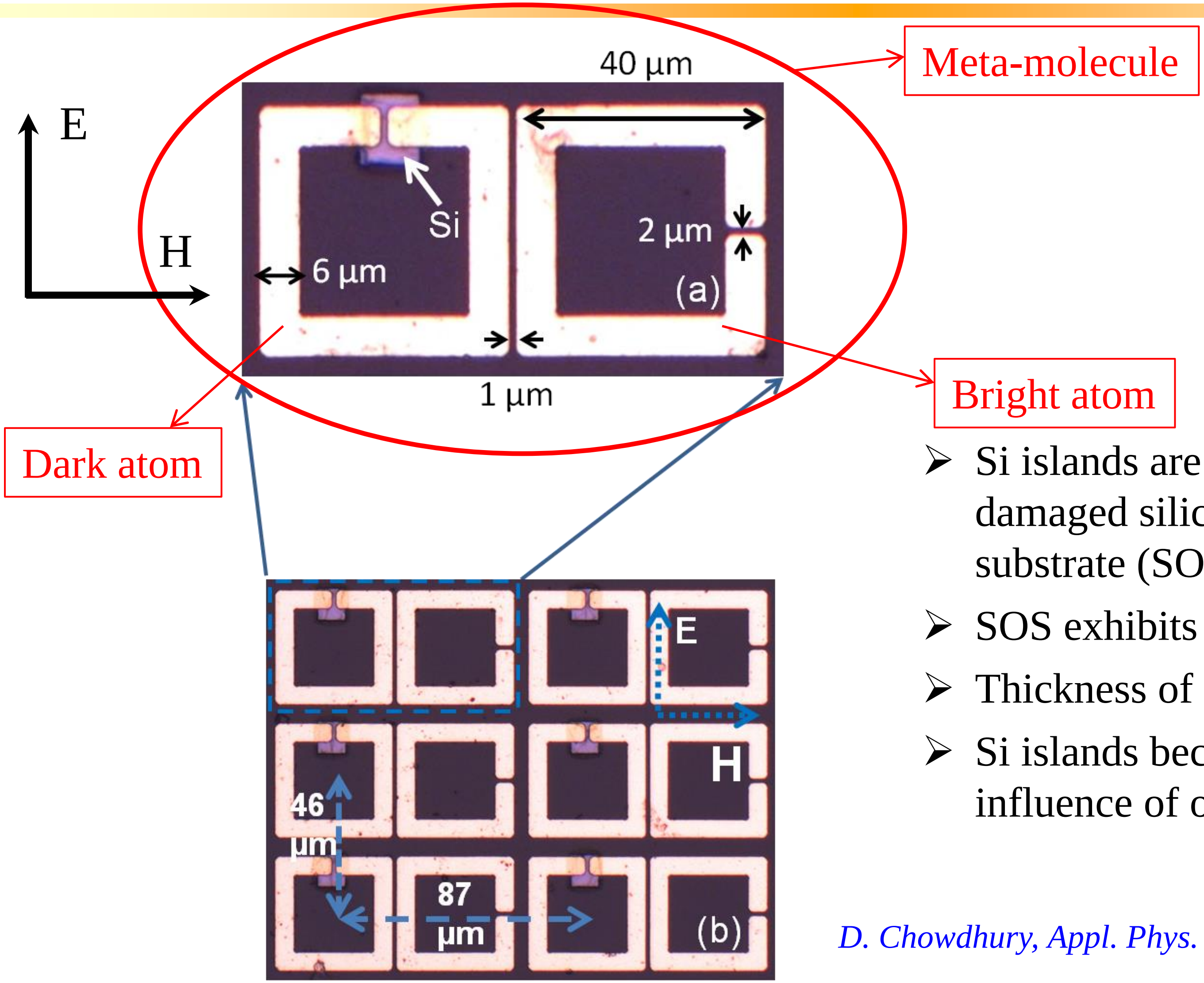
Ultrafast manipulation: dynamically modify $\omega_{0(Dark)}$

- Optical excitation by 800 nm pump
- Ultrafast electron lifetime in Radiation Damaged Silicon (RAD-Si)
- Simultaneous THz transmission spectroscopy
- At different time delay (ultrafast time scale)

consequence

With different time delay split gap conductivity of dark resonator changes, hence inter resonator magnetic coupling is modified

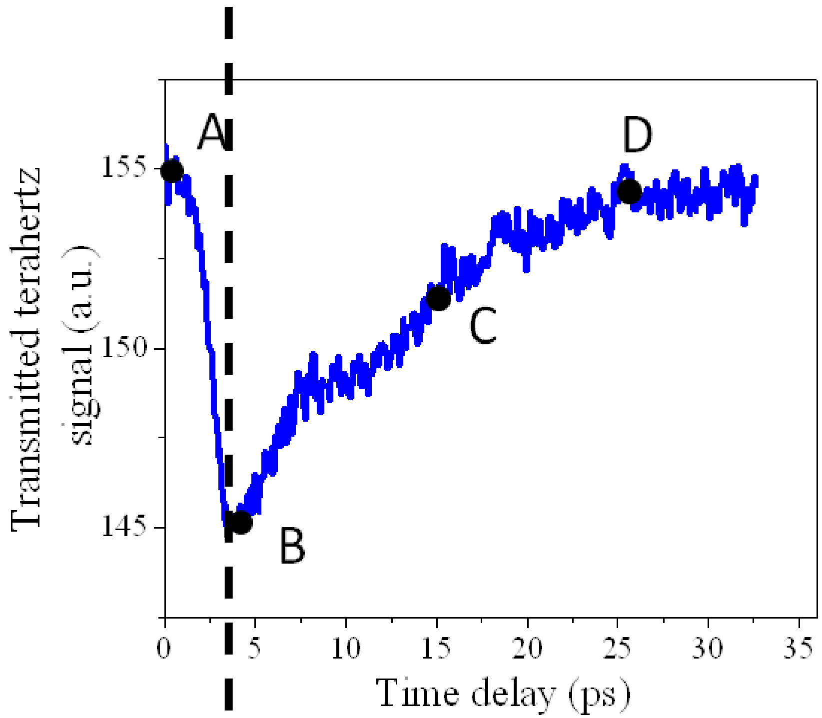
Fabricated sample

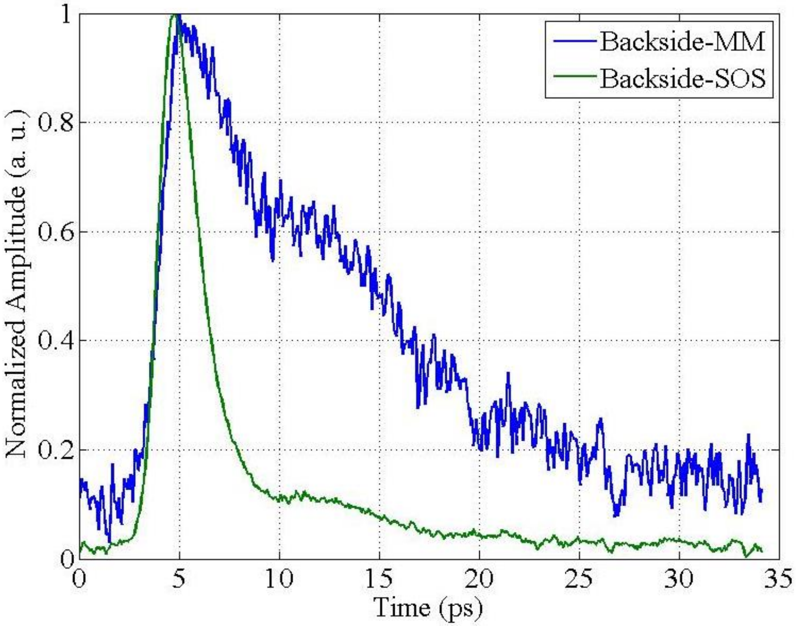


- Si islands are made from radiation damaged silicon film on sapphire substrate (SOS)
- SOS exhibits ultrafast carrier dynamics
- Thickness of silicon is 0.5 µm
- Si islands become conductive under the influence of optical excitation

D. Chowdhury, Appl. Phys. Lett. 102, 011122 (2013)

Ultrafast carrier dynamics of RD-SOS



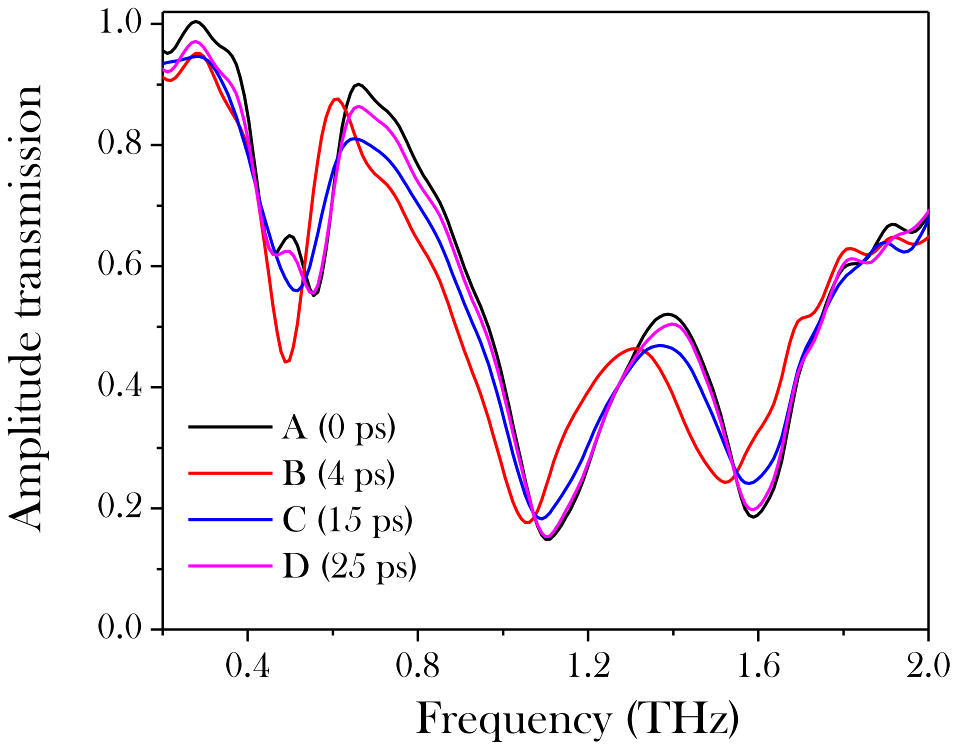


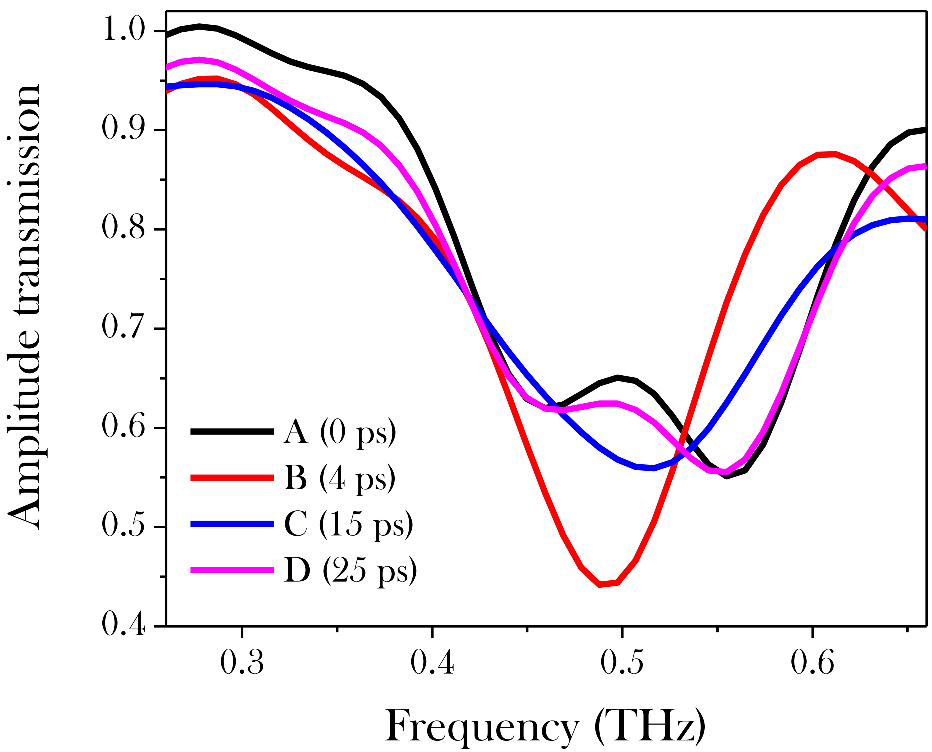
- ➢Conductivity of Si is maximum @ B
- ➢Majority of the carriers recombine @ C
- ➢Si becomes nonconductive again @ D

Carrier life times exhibit different dynamics with and without SRR structures

D. Chowdhury, Appl. Phys. Lett. 102, 011122 (2013)

Amplitude transmission at various time delay

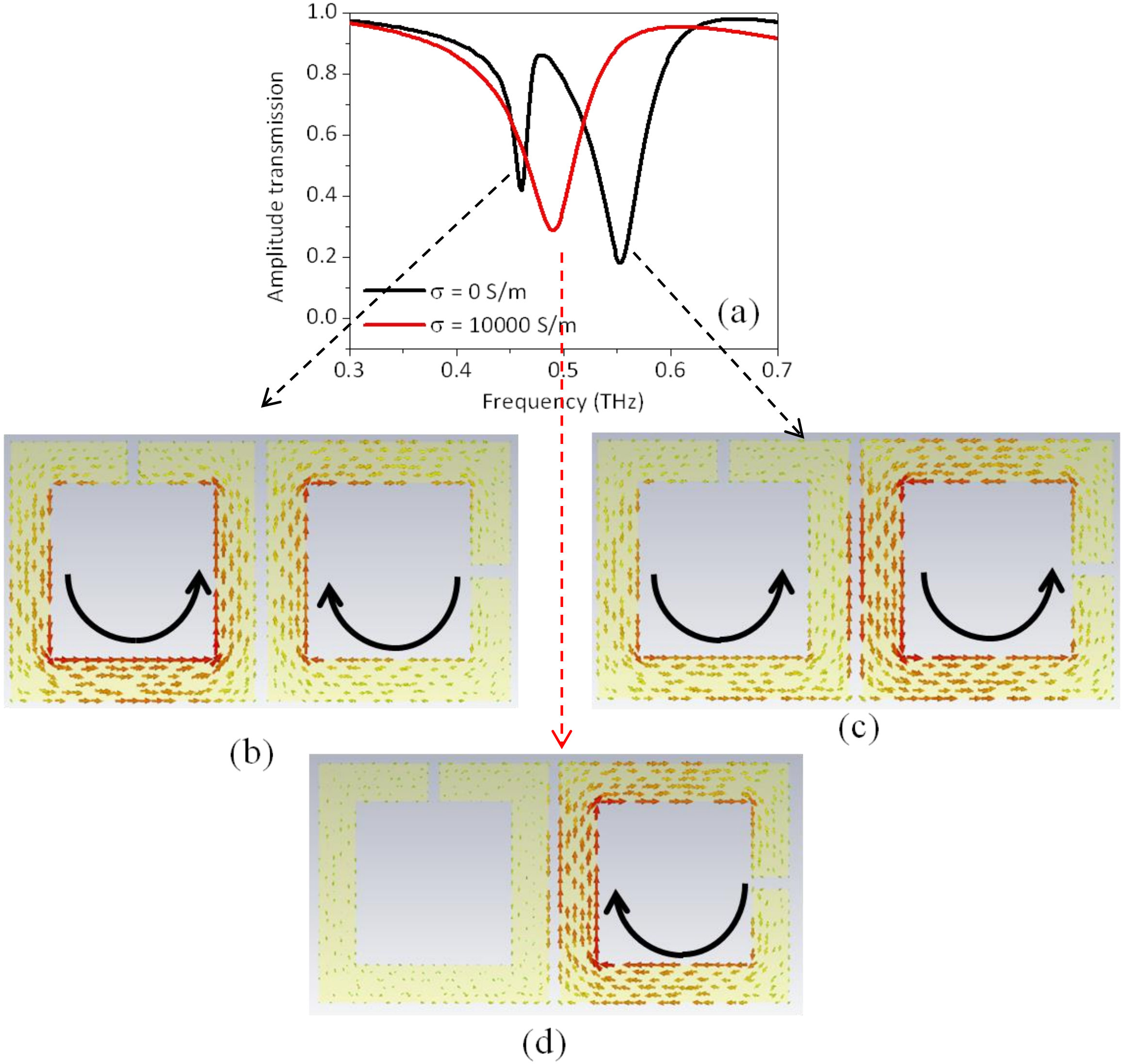




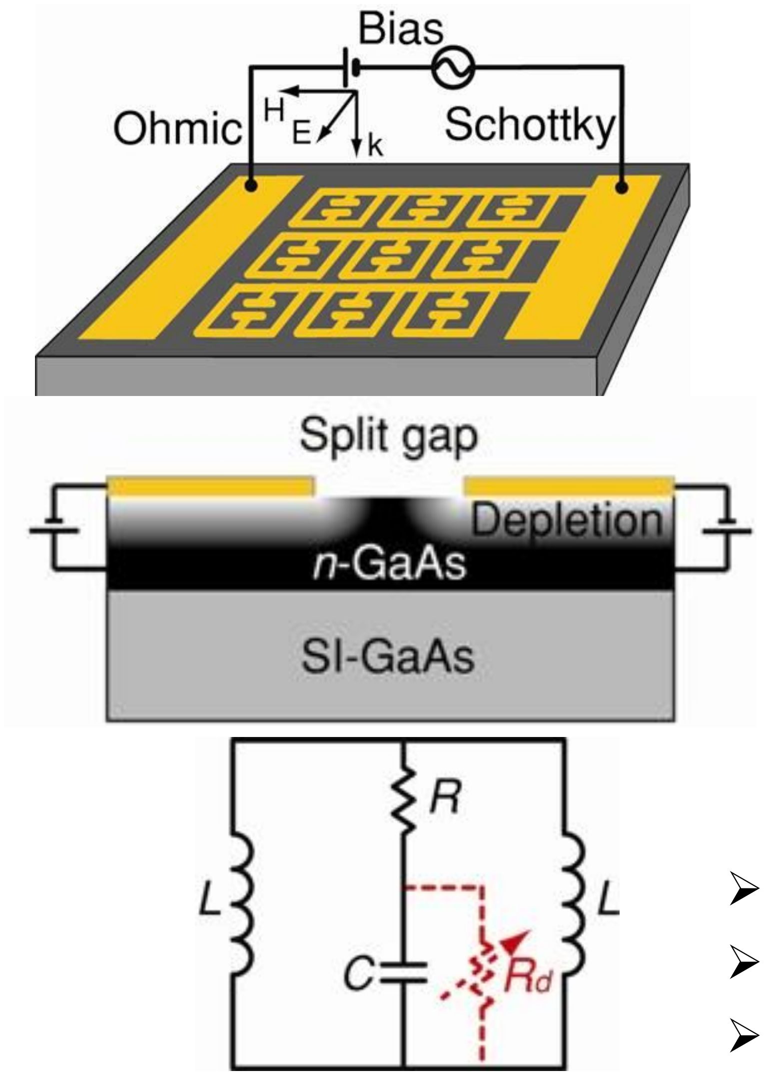
- Before optical pump pulse arrive we observe strong coupling
- At point B Si becomes conductive, dark SRRs act like CRR, and the system becomes an uncoupled system – manifested by a single resonance peak
- With time Si becomes nonconductive and the system restores the coupling nature
- Complete recovery takes ~ 25 ps

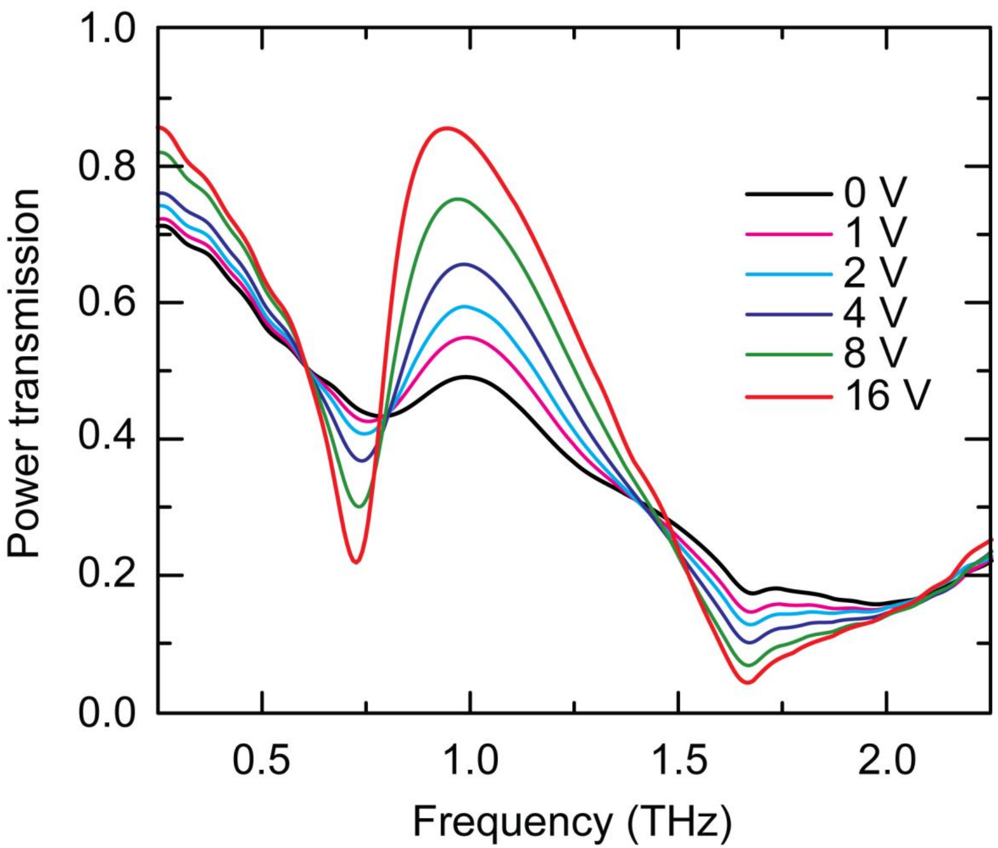
D. Chowdhury, Appl. Phys. Lett. 102, 011122 (2013)

CST Simulation with different conductivities of silicon



Electrically Controlled Modulation

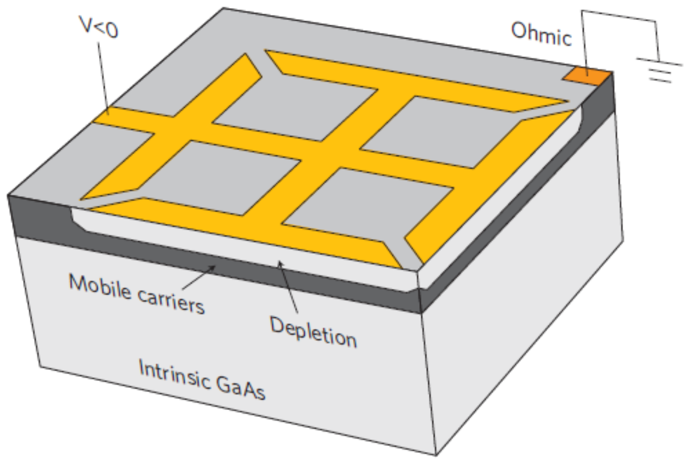


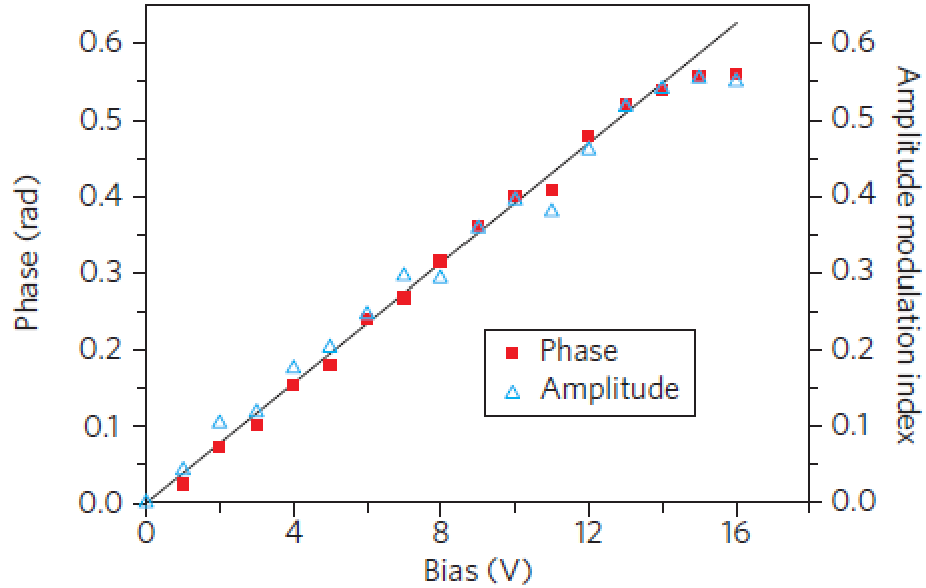


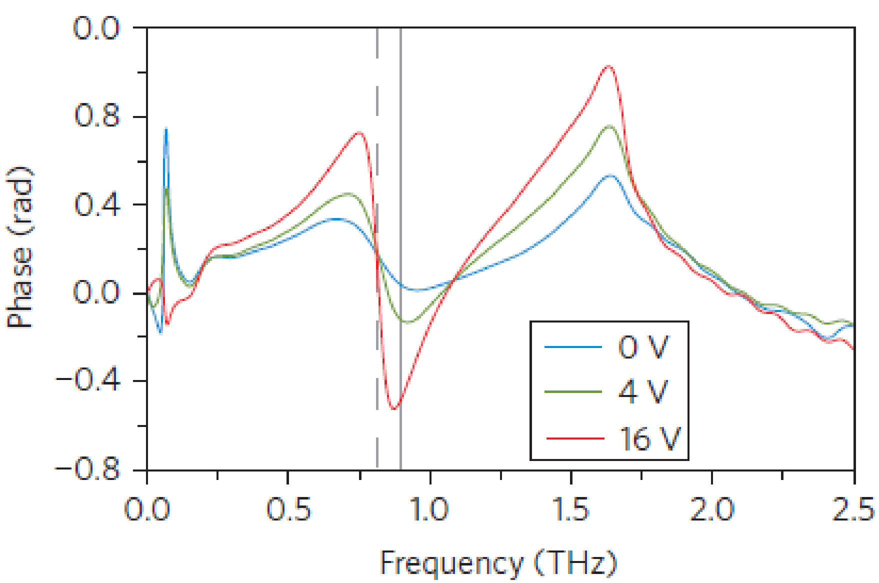
- Power modulation depth: $\Delta T/T = T_{0V} - T_{16V} / T_{0V} = 5$
- Modulation up to 2 MHz demonstrated
- Room Temperature Operation

Chen, Nature 444, 597 (2006)

Solid-state terahertz modulator



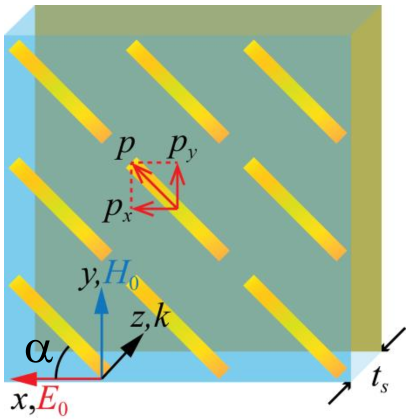




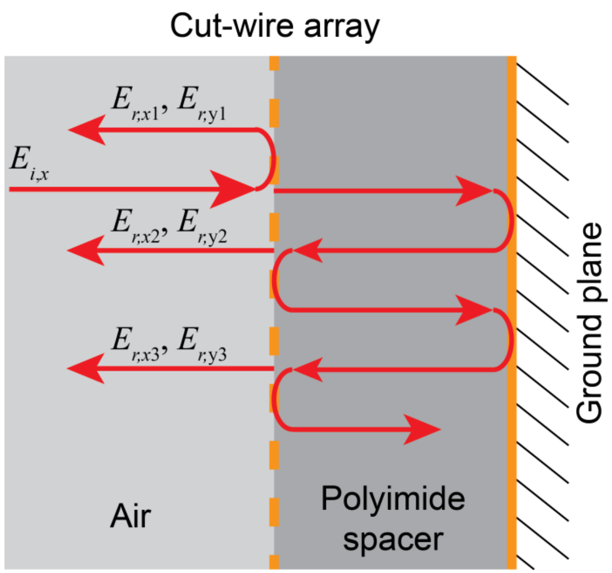
- Amplitude at 0.75 THz change linearly with bias
- Phase at 0.85 THz changes linearly
- First THz solid state phase modulator

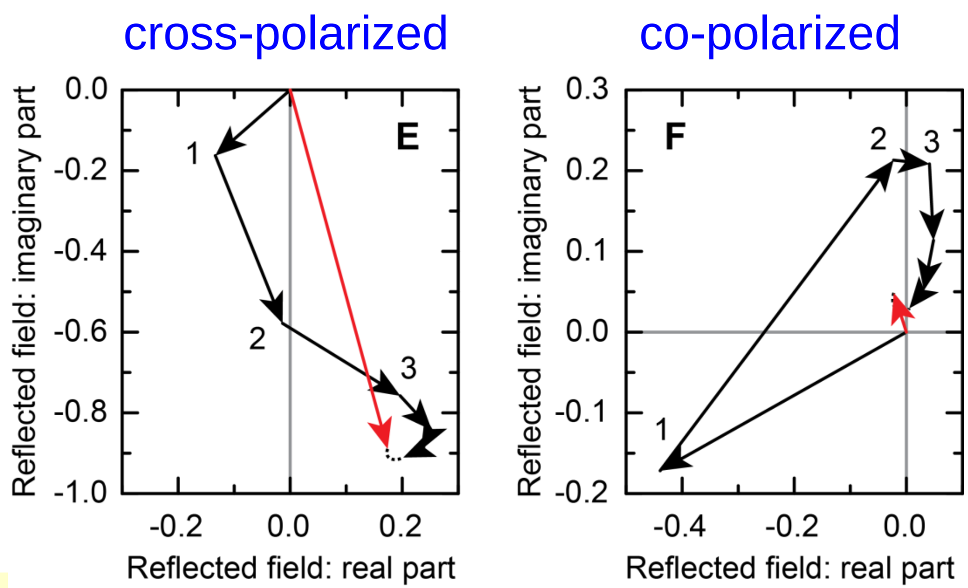
*H. Chen, Nat. Photon. **3**, 148 (2009)*

Polarization Converter: Reflection



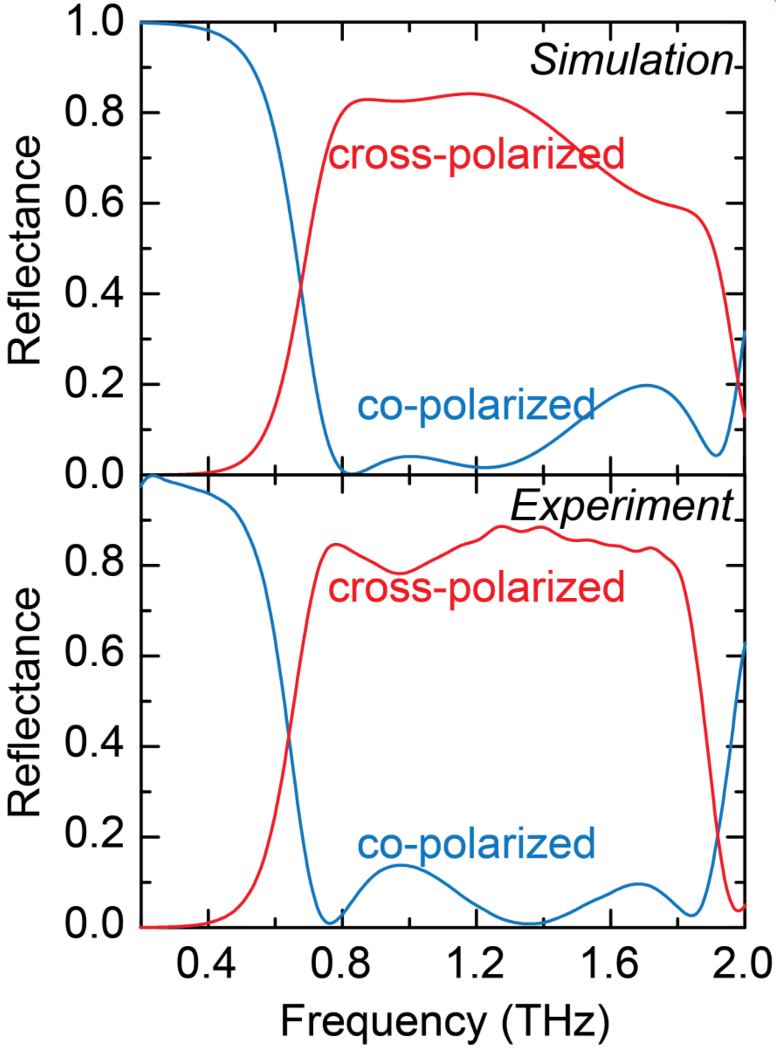
- Backed with a metal ground plane with appropriate thick dielectric spacer
- Multiple reflections contain both x and y components
- The co-polarized multiple reflections interfere destructively, leading to minimal co-polarized reflection
- The cross-polarized multiple reflections interfere constructively, leading to high cross-polarized reflection





*Grady et al., Science **340**, 1304 (2013).*

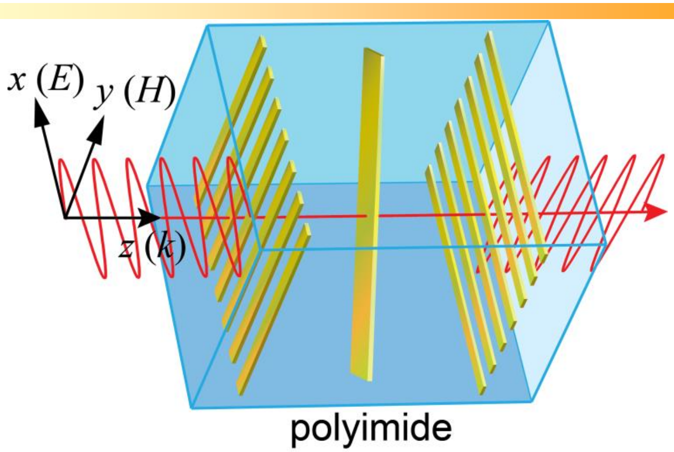
Metamaterial Polarization Converter: Reflection

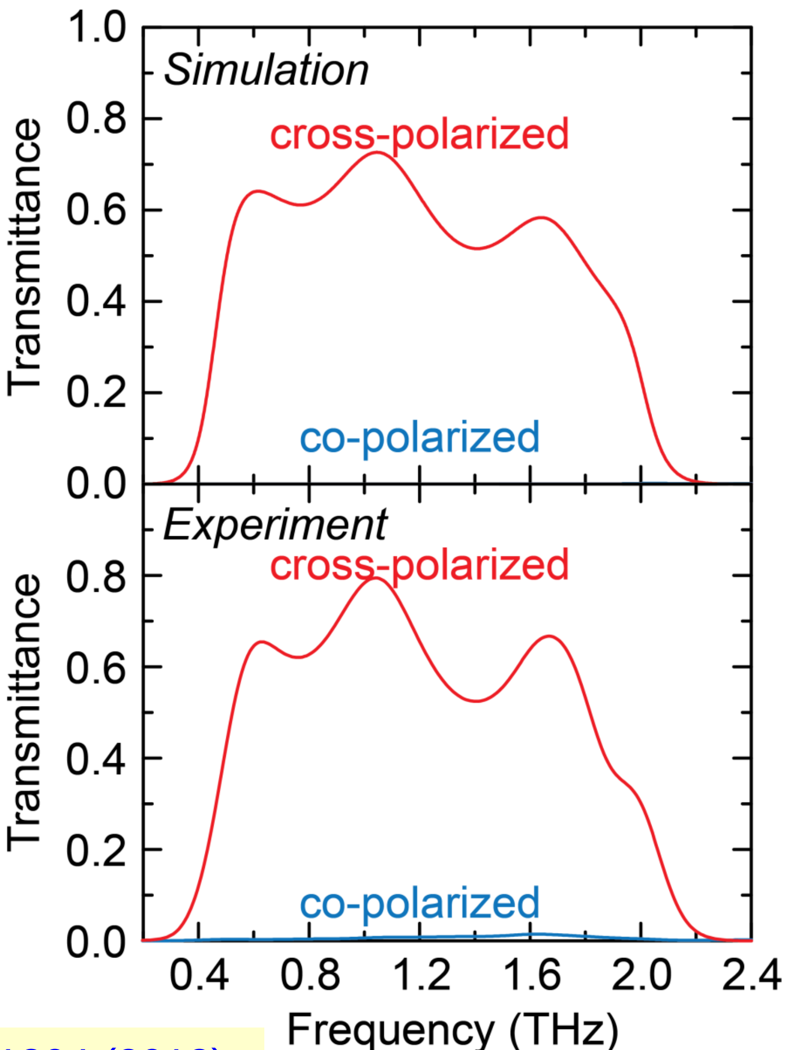


- ❑ Demonstrated in both simulations and experiments
- ❑ Device thickness 33 μm
- ❑ Co-polarized reflection is minimal
- ❑ Cross-polarized reflectance is more than 80%
- ❑ Broadband: destructive interference at multiple frequencies

Grady et al., *Science* **340**, 1304 (2013).

Polarization Converter: Transmission

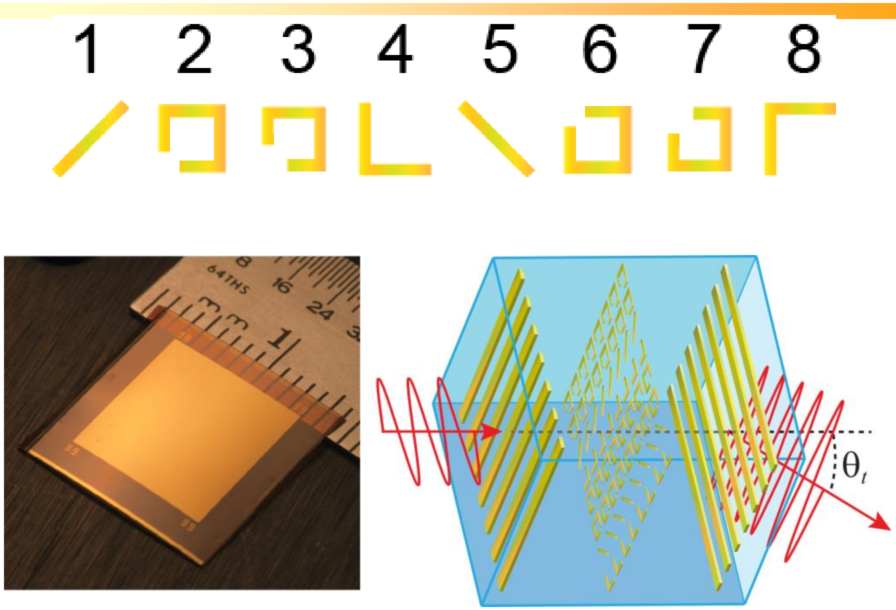


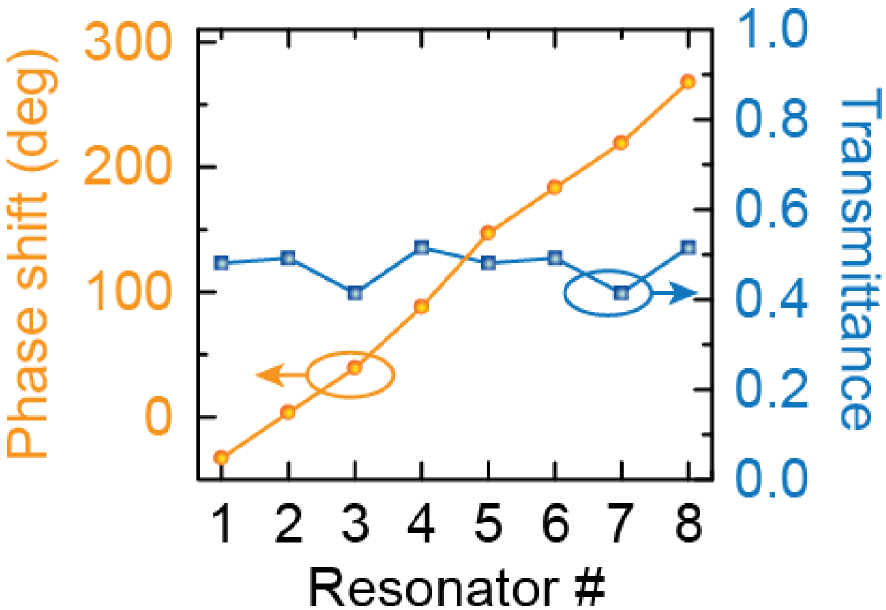


- The gratings are equivalent to ground plane for electric field polarized along the grating lines.
- The back grating prevents co-polarized light from transmitting through
- The front grating prevents the converted cross-polarized light from reflecting back

Grady et al., *Science* **340**, 1304 (2013).

Anomalous Refraction: Generalized Snell's Law



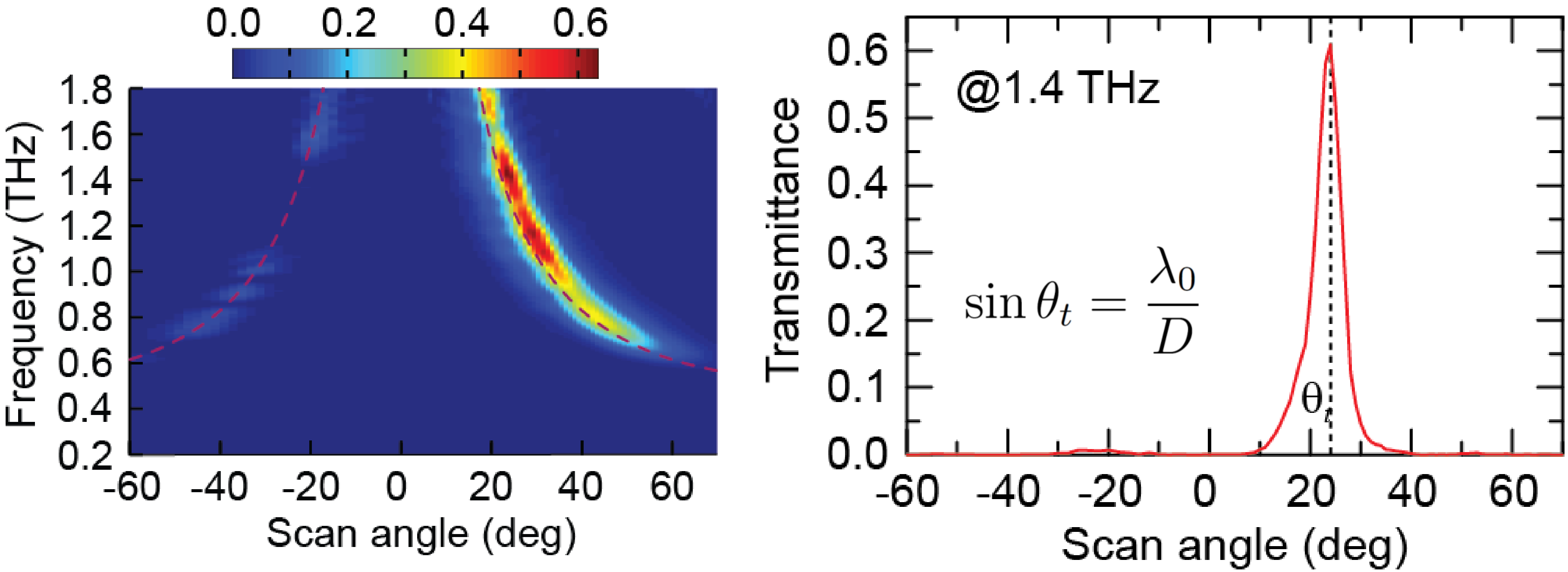


$$\sin\theta_t - \sin\theta_i = \frac{\lambda_0}{2\pi}\frac{\mathrm{d}\Phi}{\mathrm{d}x}$$

- Each individual element can be used in polarization converter
- Conversion efficiency is designed to be largely constant
- 8 elements form the unit cell, with a linear phase shift spanning a 2π range

Grady et al., *Science* **340**, 1304 (2013).

Near-Perfect Anomalous Refraction: Exp.



- At a specific frequency, the “refraction angle” is determined by periodicity
- At 1.4 THz, the anomalous refraction carries 60% of the incident power
- Measure the cross-polarized transmission *vs.* scanning angle
- Operate over a broad bandwidth

Grady et al., *Science* **340**, 1304 (2013).

Summary

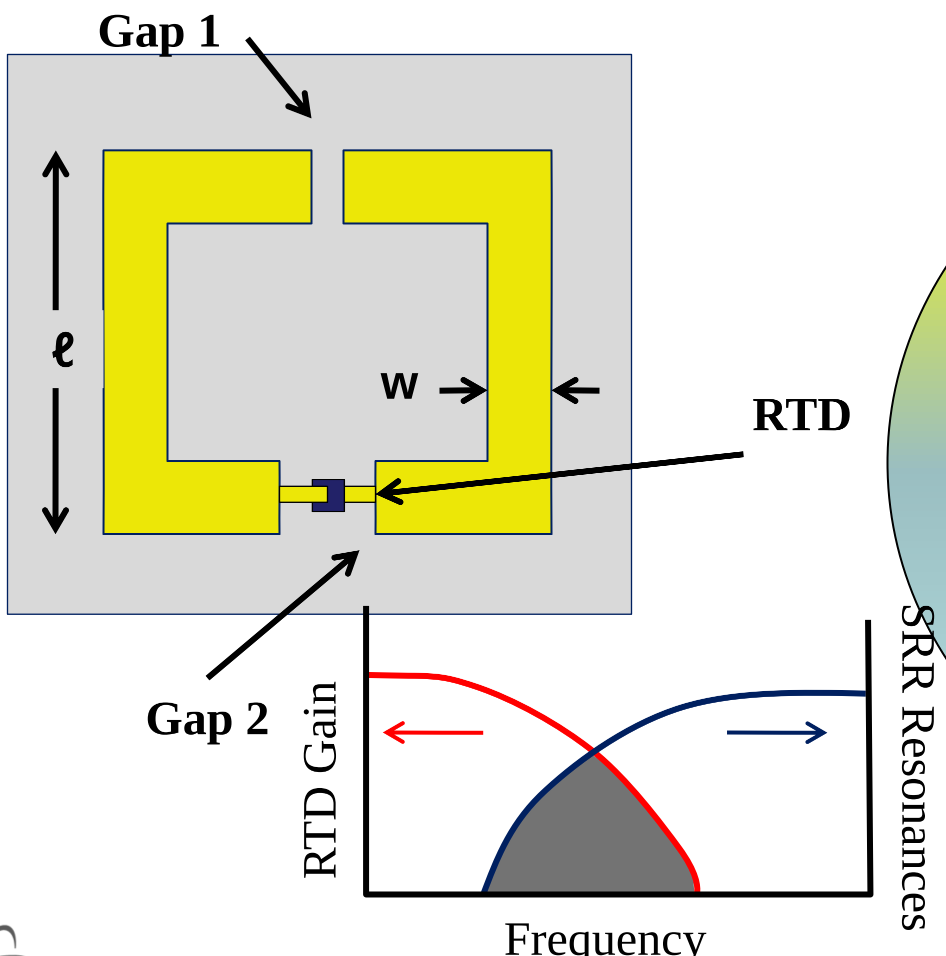
- Engineered metasurfaces at THz frequencies, Strong resonance response
- Understanding basic properties with respect to design parameters
- Investigated the coupling mechanism and the corresponding effect on resonances
- Actively modulation of THz radiation using optical controls

U.S. DEPARTMENT OF ENERGY

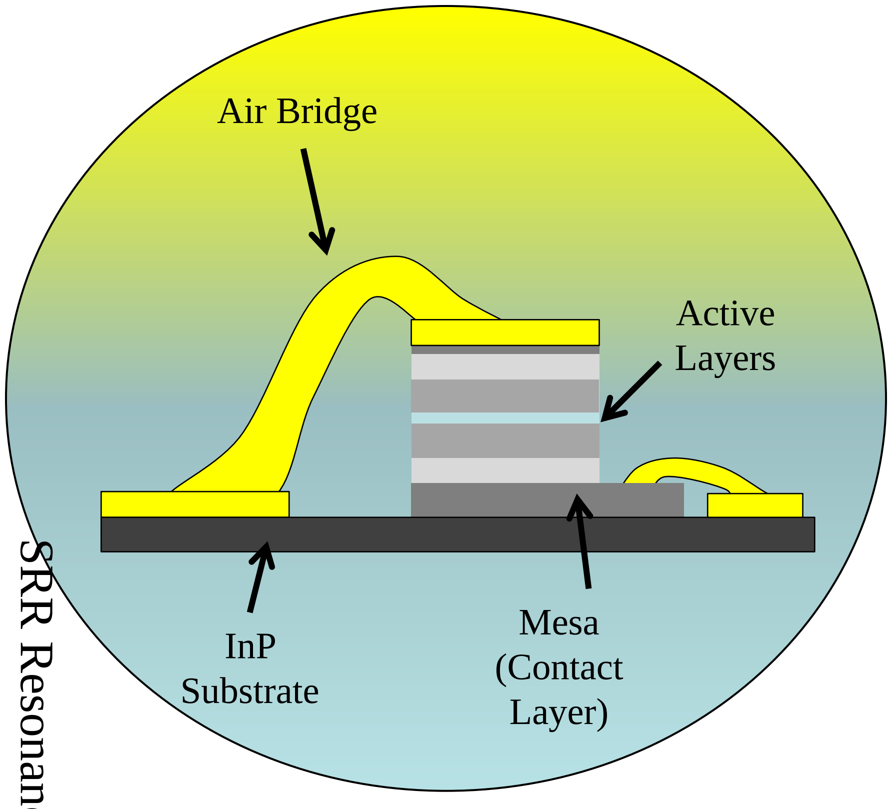
Laboratory Directed Research & Development

Electrical Generation of Microwave and THz

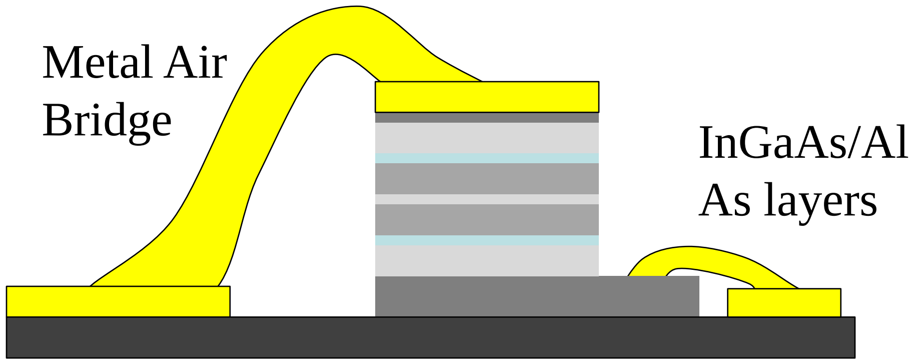
Split Ring Resonator acts as a tank circuit providing feedback and antenna

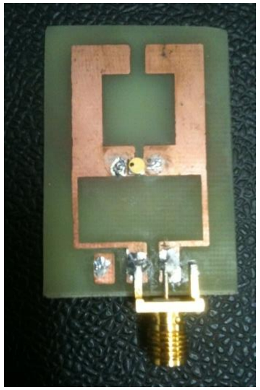


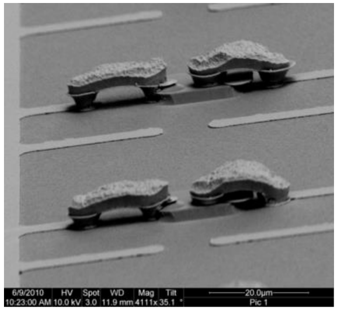
Resonant Tunneling Diode (RTD) is active gain element

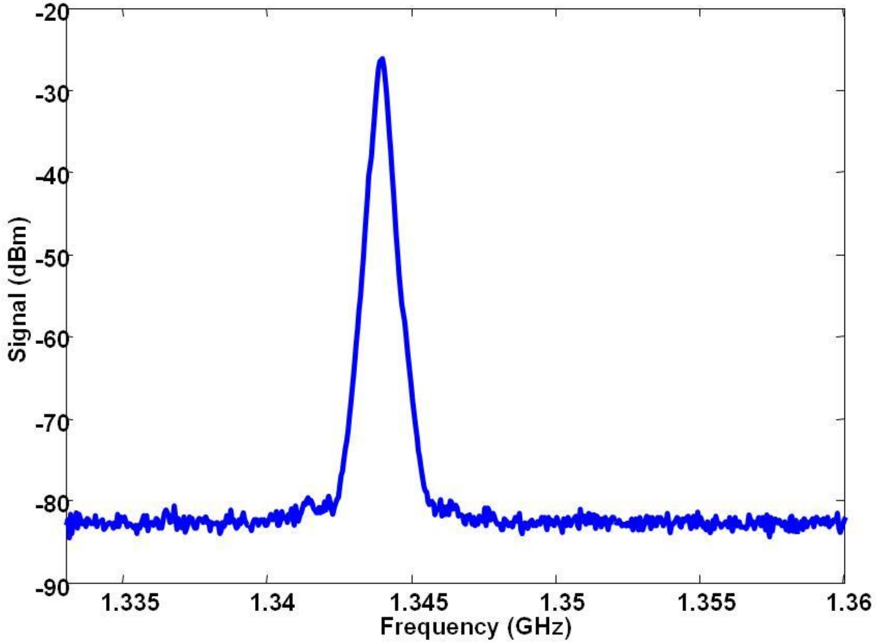


Electrical Generation of Microwave and THz









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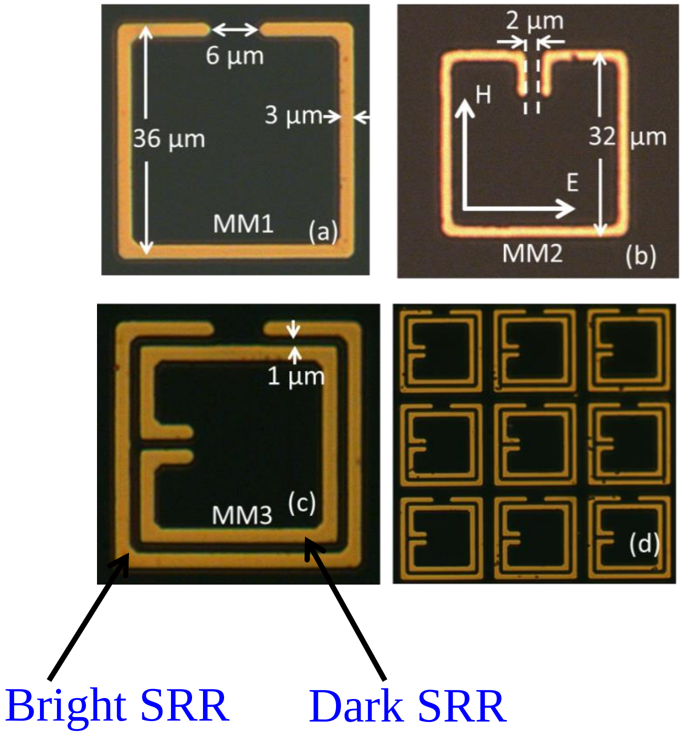
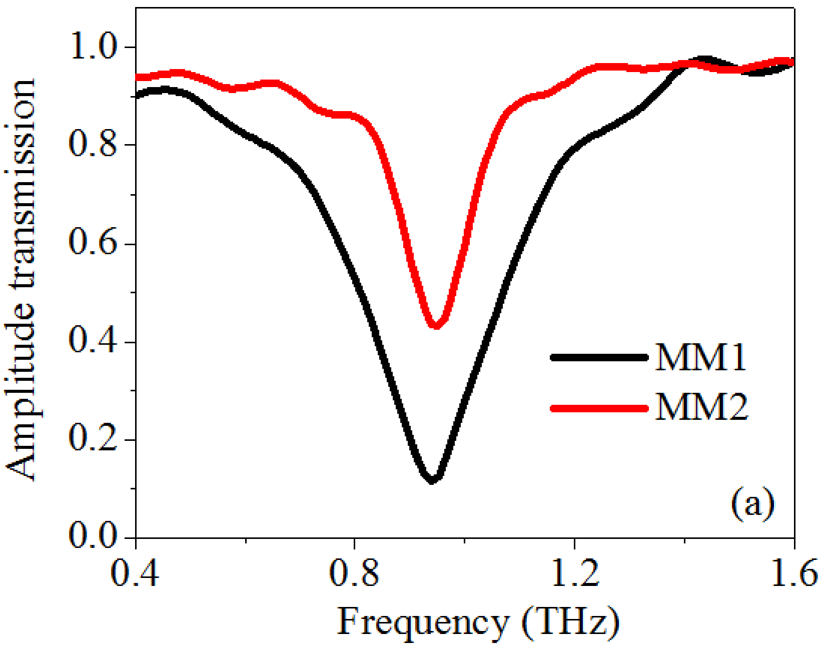
My special thanks to

Professor Dr. Y. Haider
Professor Dr. Monowar Abedin

Strongly coupled planar metasurface

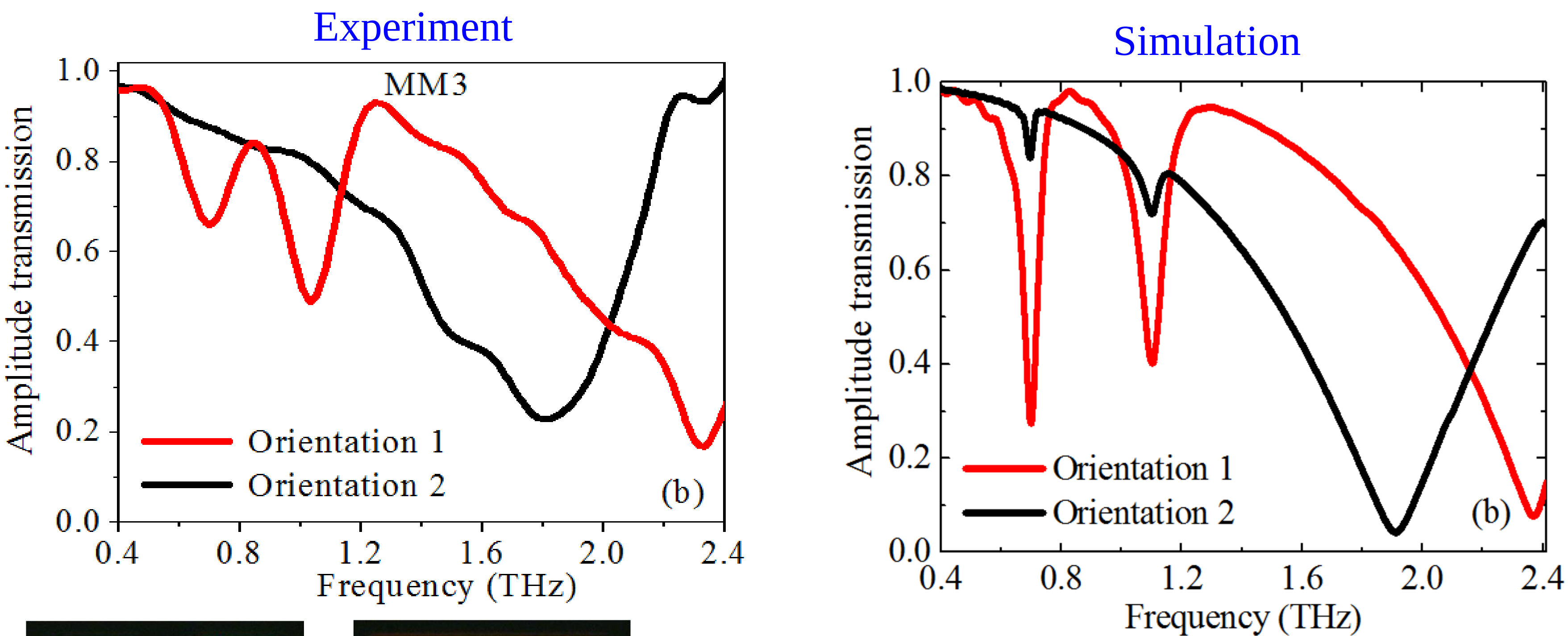
- Meta-atom based meta-molecule
- Meta-atom can be bright or optically active for certain polarization or dark
- Strong coupling can be realized through concentric configuration

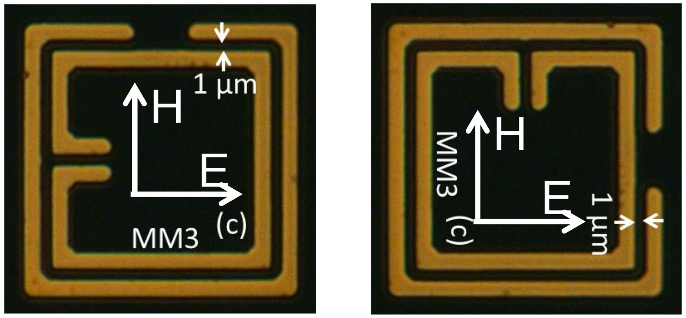




D. R. Chowdhury et al., Appl. Phys. Lett. (Accepted)

Strongly coupled planar metasurface

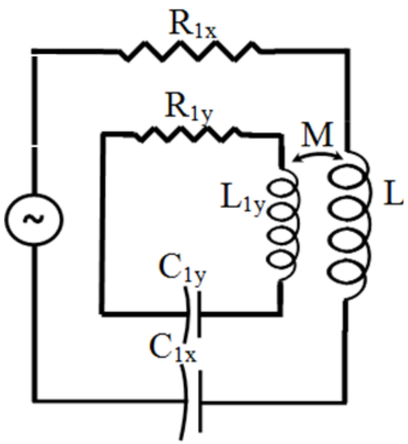




- Strong anisotropy
- Mutual coupling between inner and outer ring varies with orientation???

D. R. Chowdhury et al., Appl. Phys. Lett. (Accepted)

Strongly coupled planar metasurface



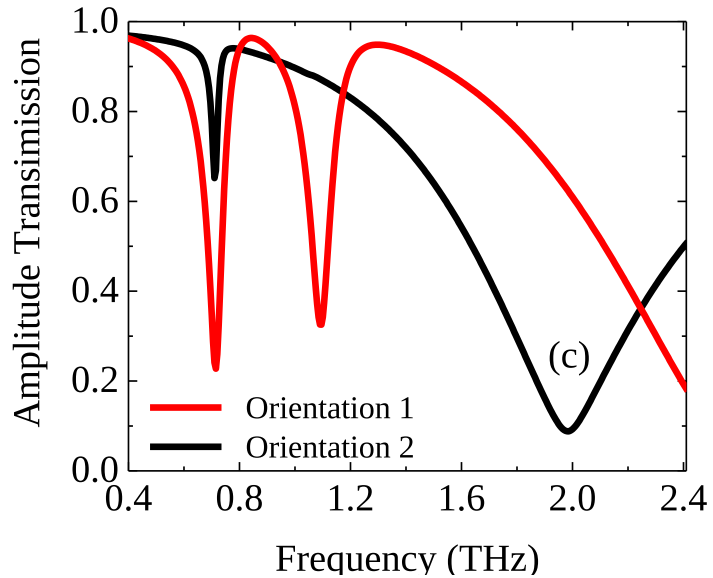
MM1 active

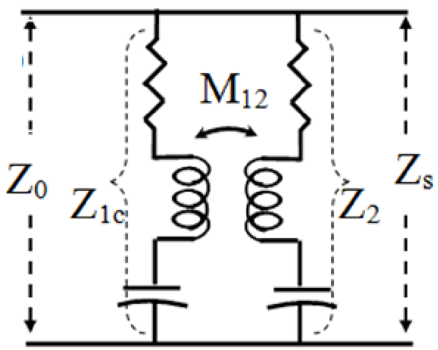
$$Z_{1xc} = Z_{1x} + \frac{\omega^2 M^2}{Z_{1y}}$$

MM2 active

$$Z_{1yc} = Z_{1y} + \frac{\omega^2 M^2}{Z_{1x}}$$

Analytical



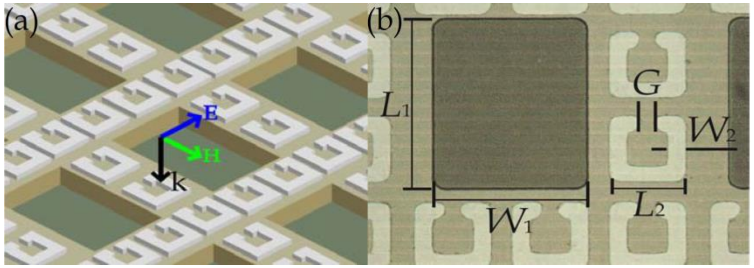


$$Z_{tot} = \frac{Z_{1c}Z_2 + \omega^2 M_{12}}{Z_{1c} + Z_2 + j\omega 2M_{12}}$$

- Coupling between LC resonances of MM1 and MM2
- Stronger coupling creates larger frequency separation
- Coupling between the splitted mode and the higher order modes

D. R. Chowdhury et al., Appl. Phys. Lett. (Accepted)

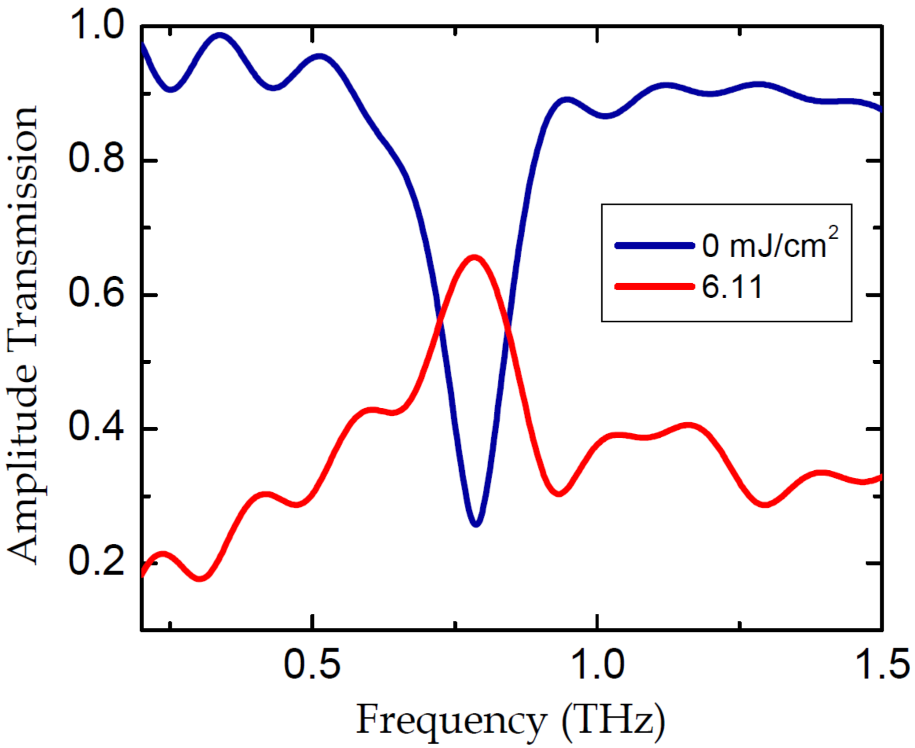
An active hybrid plasmonic metamaterial



L_1 = 65 µm, W_1 = 50 µm, L_2 = 33 µm, W_2 = 6 µm, and G = 5 µm

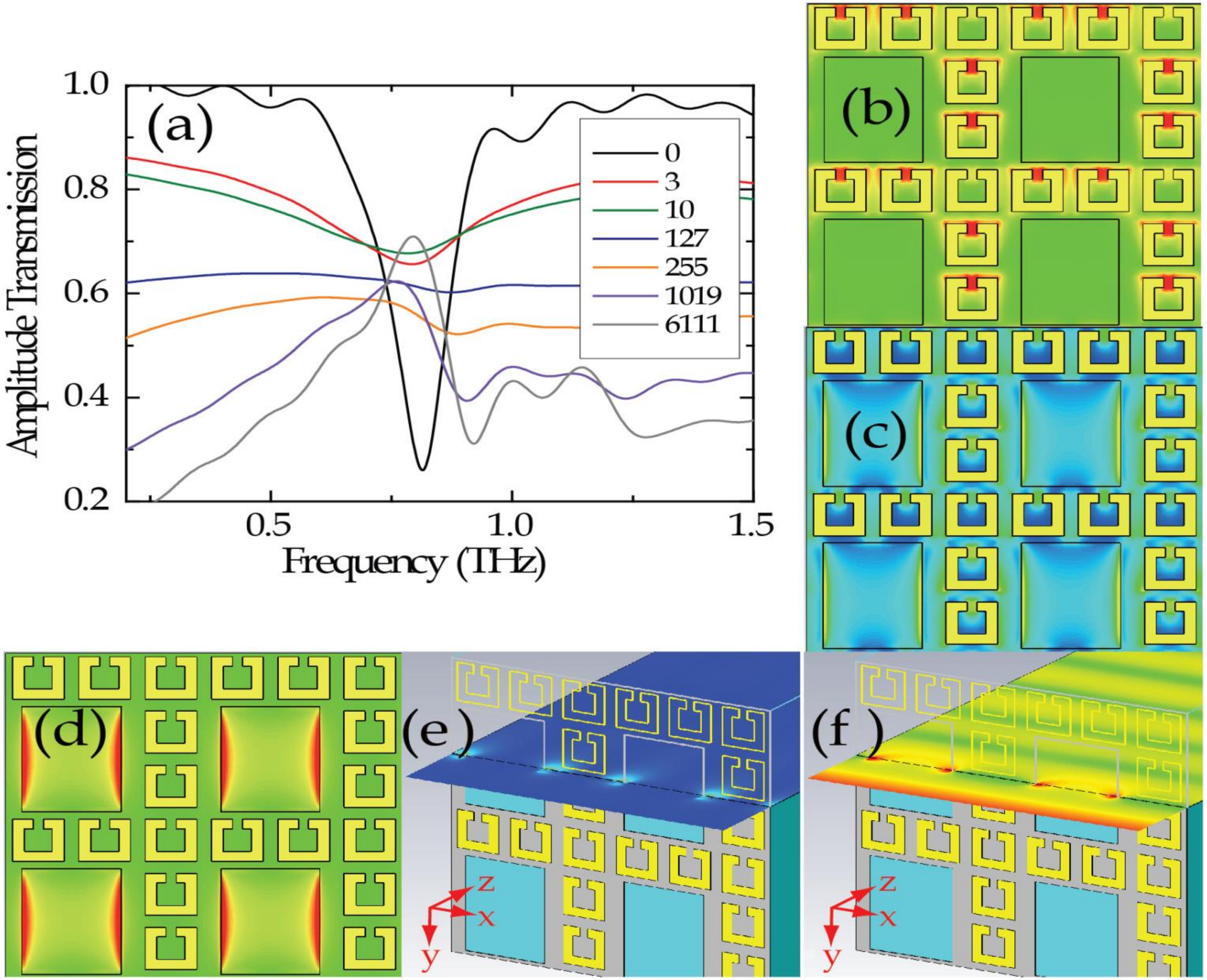
- Substrate: Silicon on Sapphire
- SRR: Aluminum (200 nm)
- Silicon film thickness: 500 nm
- Plasmonic hole array: Etching silicon

J. Gu, et. al, OPTICAL MATERIALS EXPRESS 2, 1617 (2012)

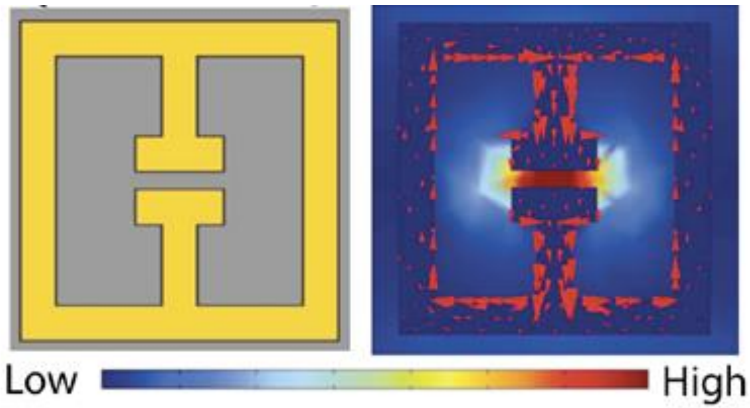


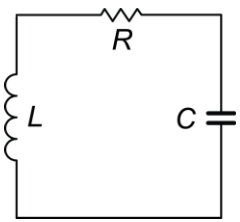
- Without optical pump: SRR resonance – band-stop nature
- With optical pump: Silicon becomes metallic
- Behaves like a metallic hole array
- Excites surface plasma polaritons, band-pass resonance

An active hybrid plasmonic metamaterial



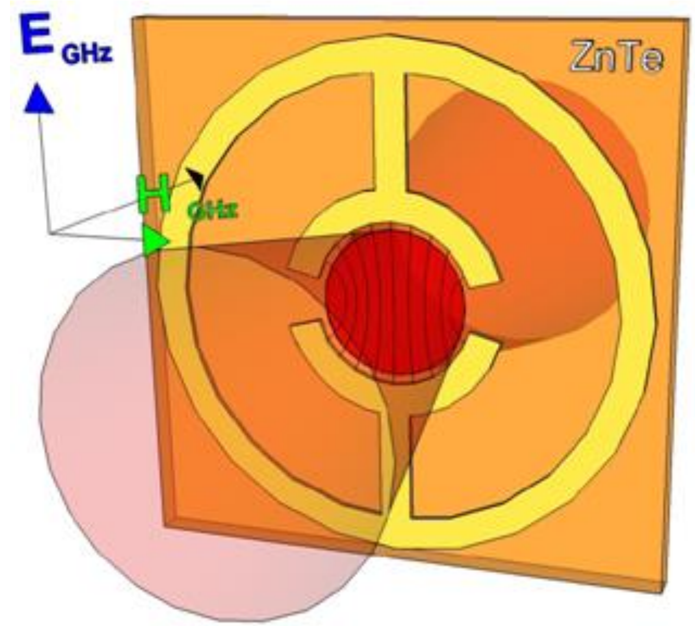
Metamaterial Electro-Optical Modulator





$$\omega \propto \sqrt{\frac{1}{LC}}$$

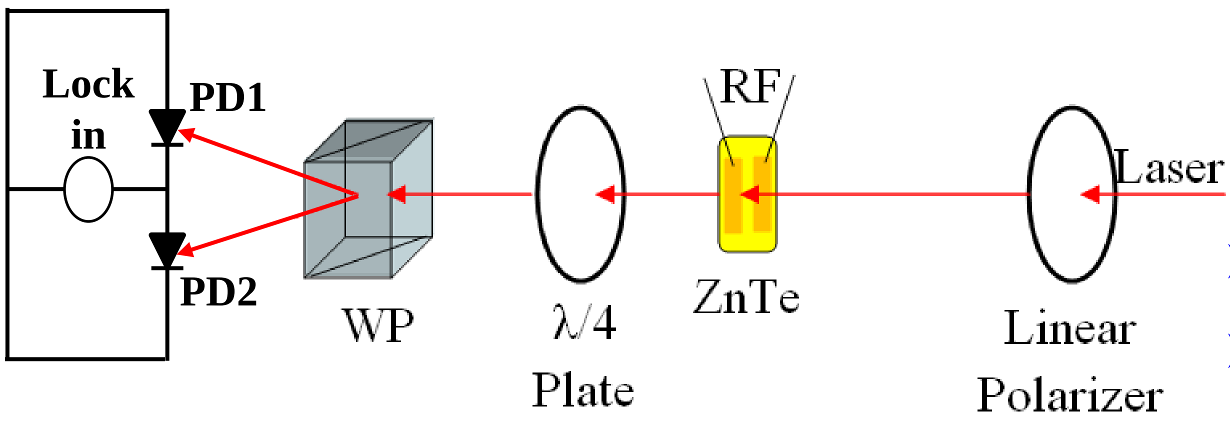
- SRR can be excited by E & H fields
- At resonance field in the gap is orders of magnitude higher than excitation field
- Ideal for EO modulator



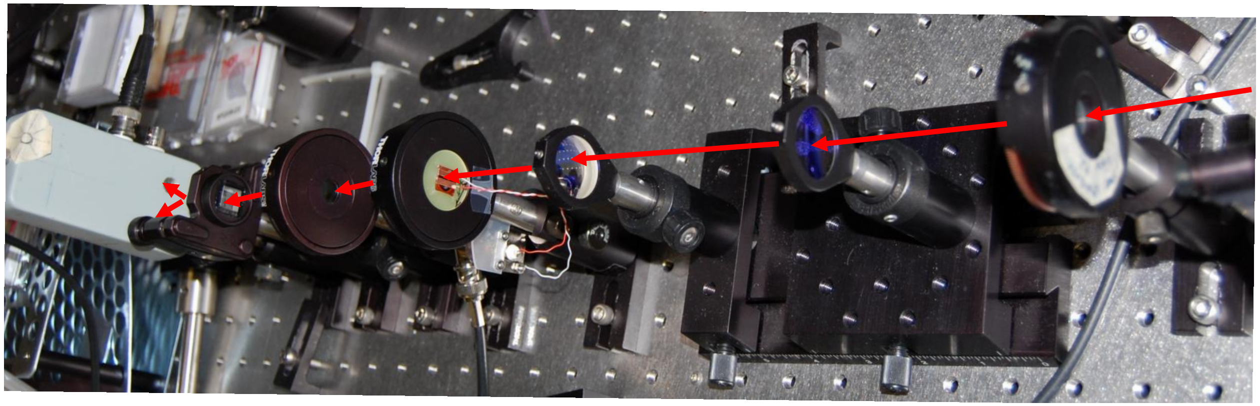
- Schematic of modulating IR light by microwave electric field
- SRR is designed to resonate at GHz frequencies
- Fabricated on an electro-optic medium

D. Shchegolkov, et. al. Submitted to Appl. Phys. Lett

Experimental setup (EO modulation)

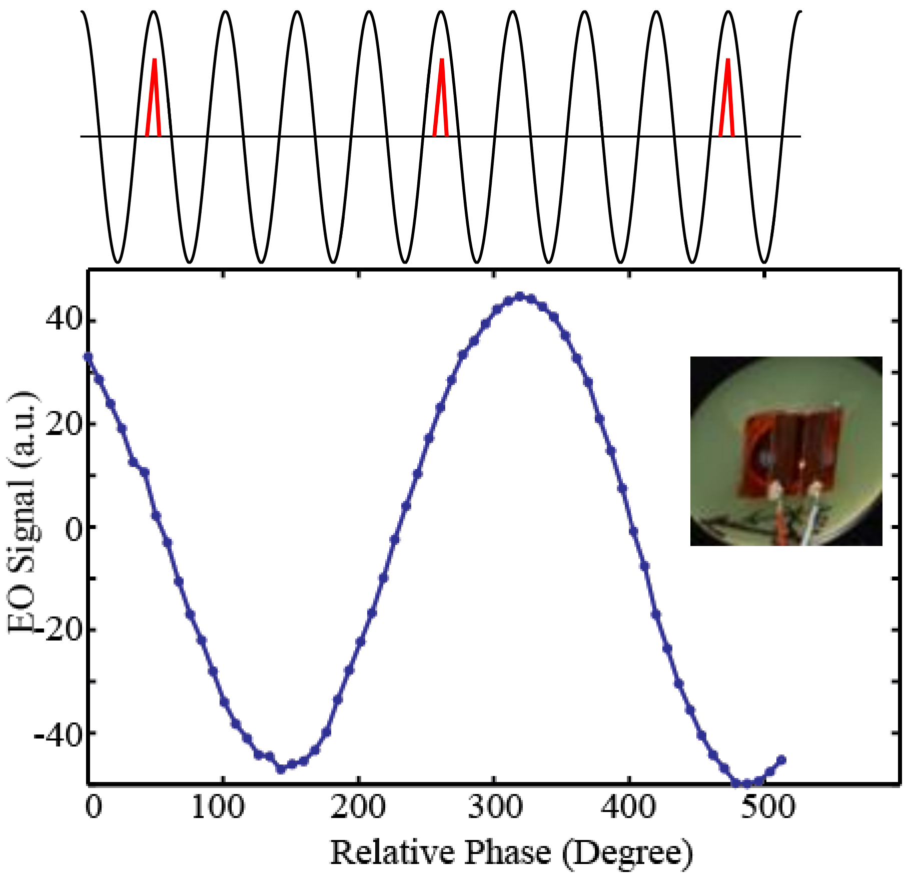


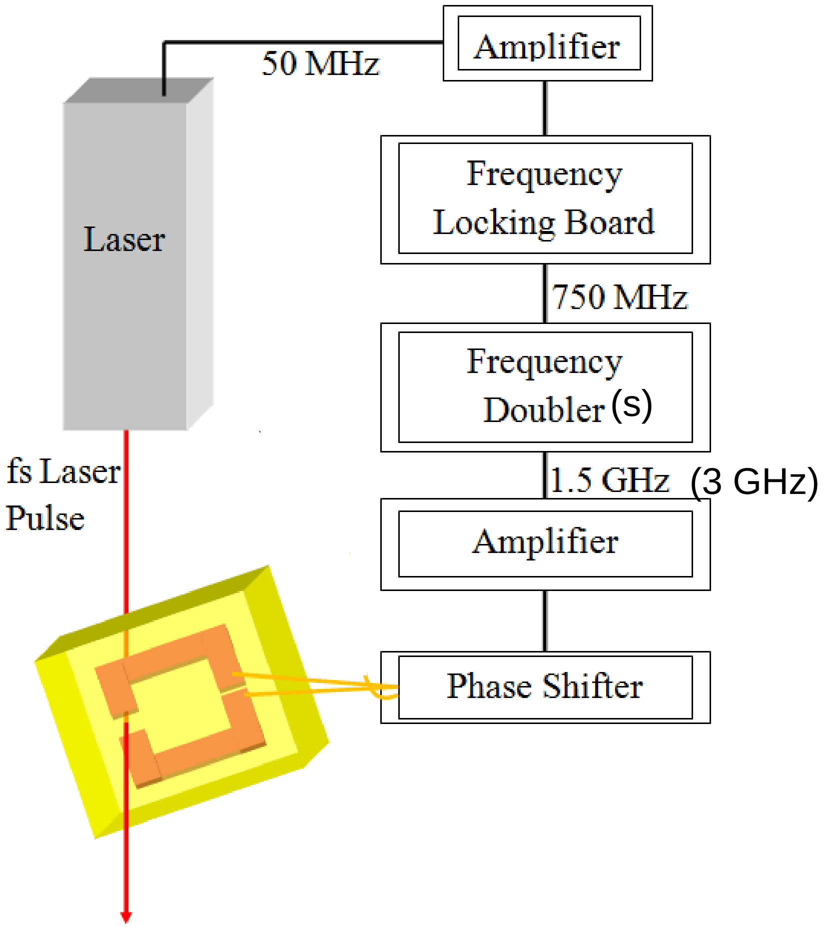
- Laser wavelength=750 nm
- Laser power: 8 mW
- Pulse width: 80 fs
- Repetition Rate: 50 MHz



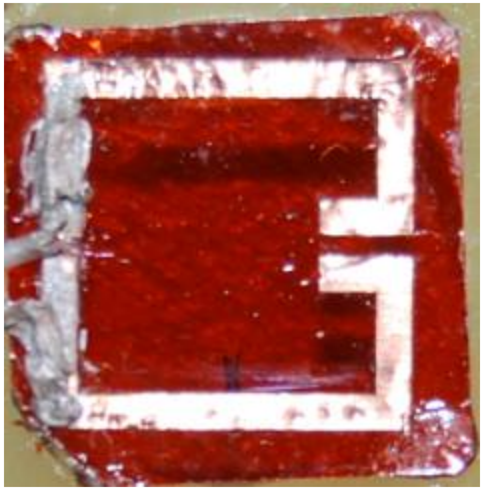
Synchronization of laser pulses with microwave signal

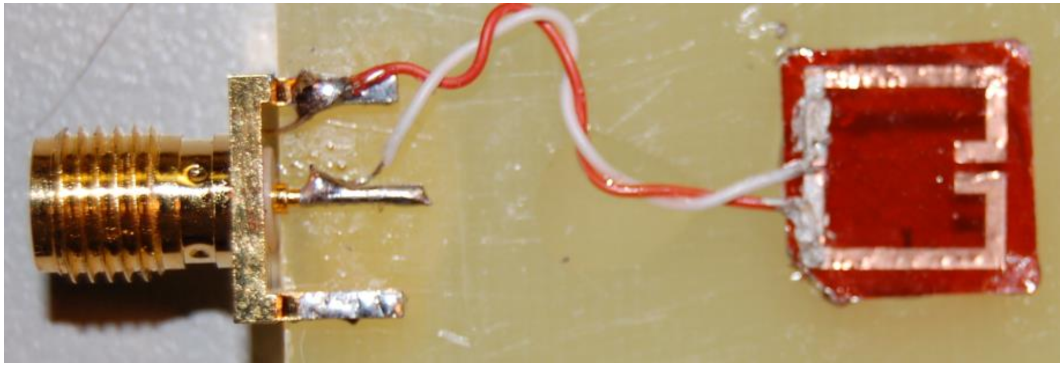
The phase of the microwave needs to be the same for each fs laser pulse.



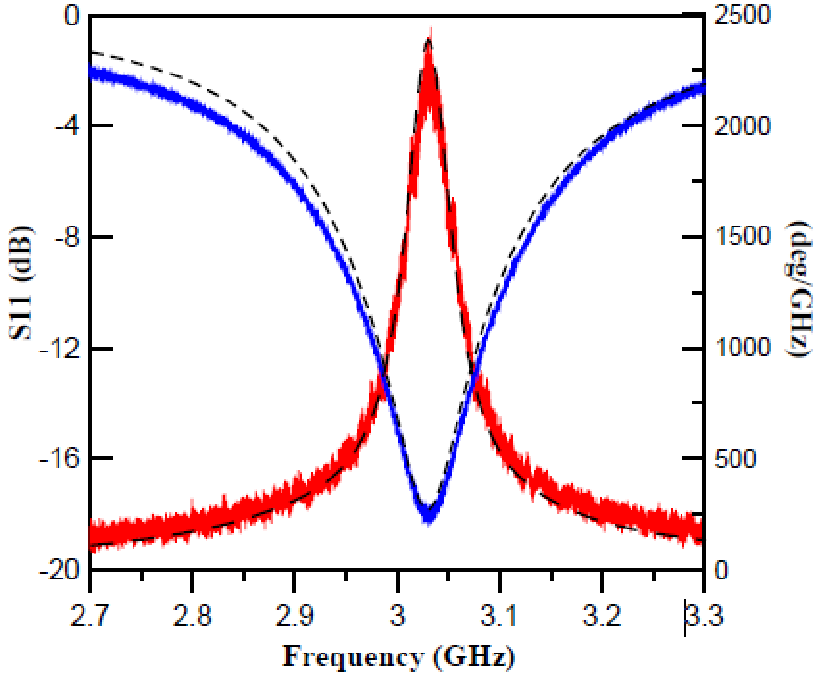


SRR Fabrication

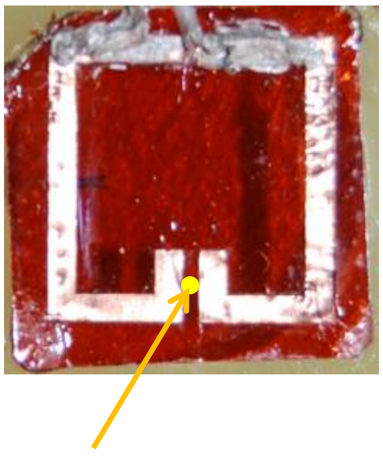


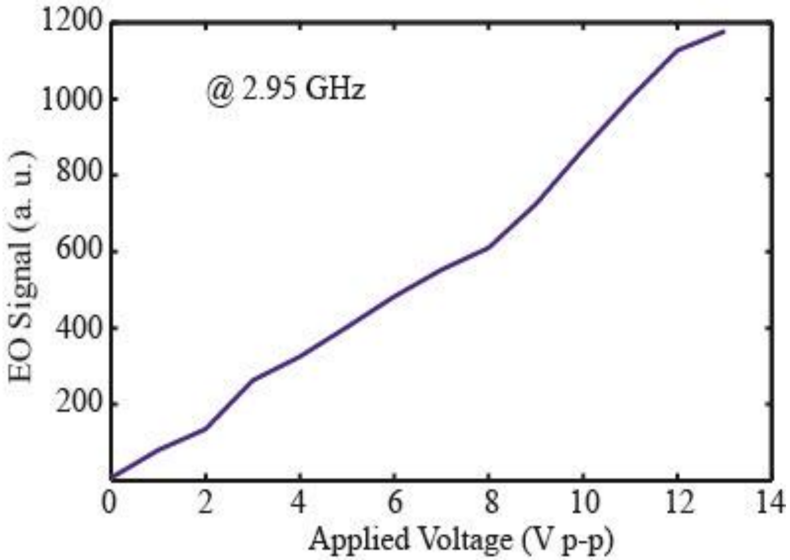


- Skin depth of copper at 3 GHz is ≈2 μm
- Used short pulse laser machining
- Laminate whole crystal with adhesive copper tape
- Etch copper



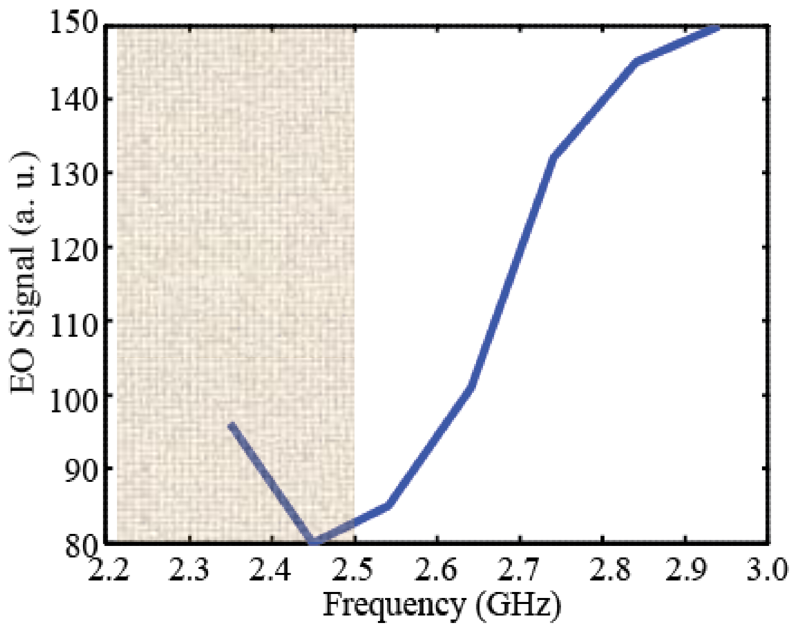
EO Measurement

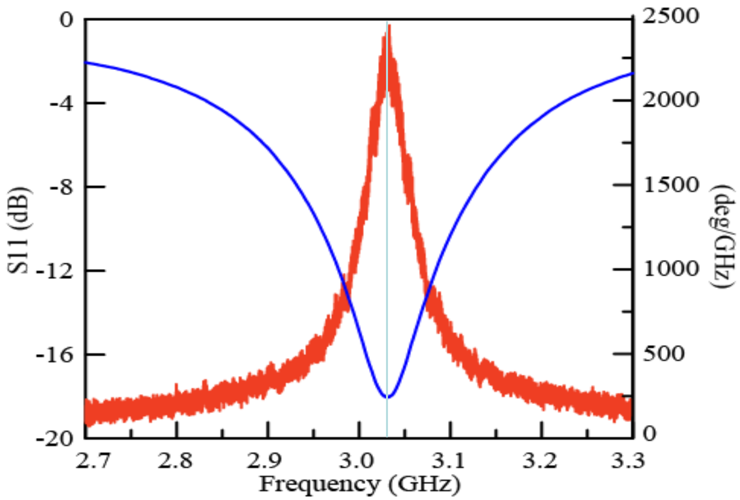




- Frequency of microwave is fixed @ 2.95 GHz
- Probe at the middle of the resonant gap
- Optical beam diameter on the sample is ~100 μm
- EO signal increases linearly with applied voltage

Frequency dependence of EO signal

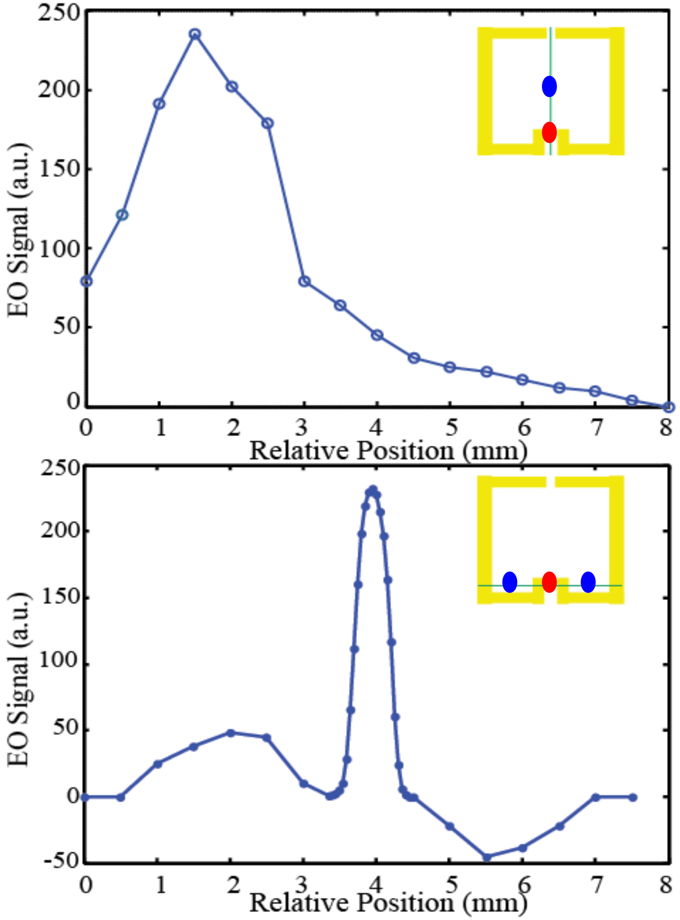




VNA Measurement

- Keep the applied voltage p-p amplitude the same
- 2.5-3.0 GHz is the specified PC board operational frequency range
- EO signal rolls-off as the microwave frequency offsets from the resonance of the SRR
- Qualitatively follows simulated voltage in the gap

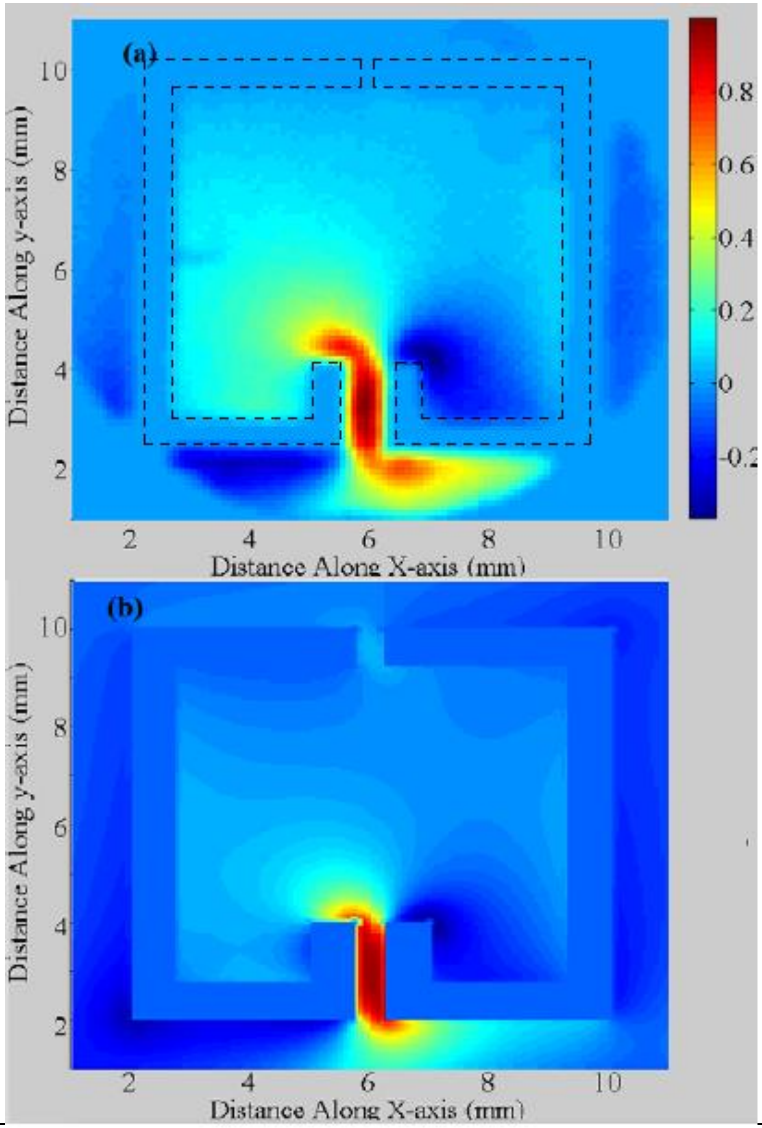
Spatial distribution of EO signal: experiment

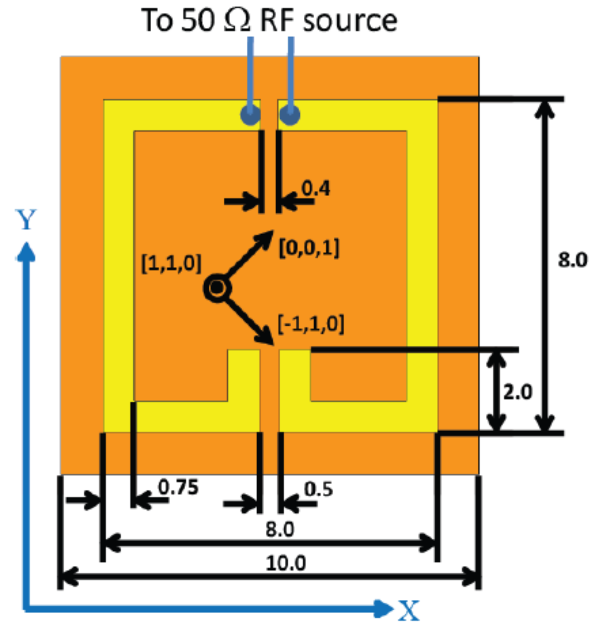


- EO signal in the SRR gap is five times higher compared to signal at the SRR center
- Horizontal scanning shows the presence of orthogonally polarized electric filed component on both sides of the gap
- Field enhancement is the highest inside the gap

Q≈7

2D Field distribution





$$\Gamma = \frac{\pi d}{\lambda_0} n_0^3 r_{41} E_{rf} \sqrt{1 + 3cos^2\alpha}$$

$$I = \rho \frac{\pi d}{\lambda_0} n_0^3 r_{41} E_{rf} |E_0|^2 sin\alpha$$

Summary

- Engineered Metamaterials at THz frequencies, Strong resonance response
- Understanding basic properties with respect to design parameters
- Investigated the coupling mechanism and the corresponding effect on resonances
- We are able to actively modulate THz radiation using optical and thermal controls
- Demonstrated metamaterial based EO modulator

Team and Collaborators

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Boston College: Willie Padilla

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Sandia National Laboratory: Igal Brener, Mark Lee, Michael Cich

Duke University: David Smith, Nan Jokerst

Center for Integrated Nanotechnologies

Los Alamos National Laboratory

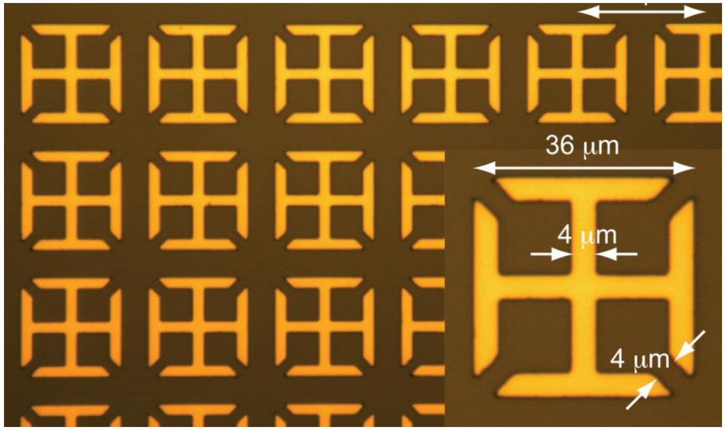
"One scientific community focused on nanoscience integration"

Sandia National Laboratory

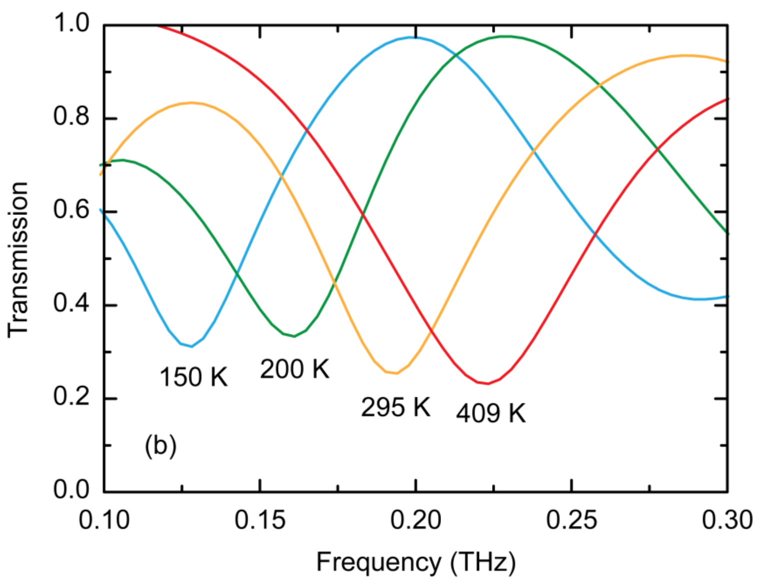
- State-of-the-art facilities
- Goal: Develop innovative approaches for nano-scale integration

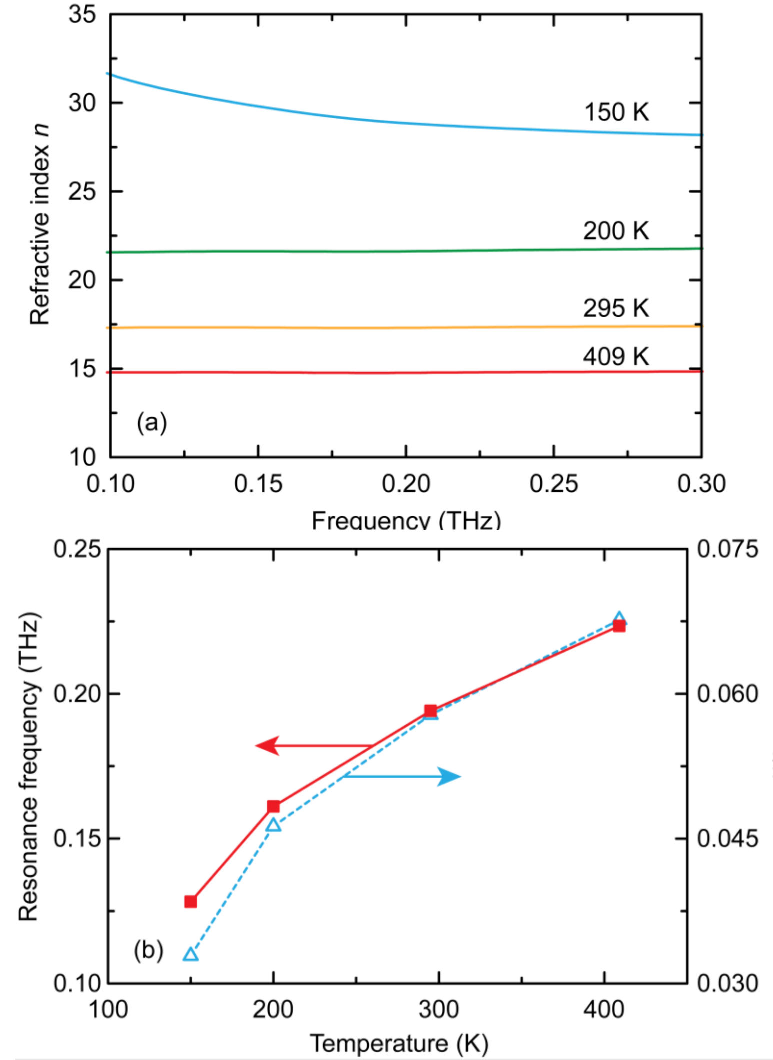
http://CINT.lanl.gov

Thermal tunability of THz metamaterials using $SrTiO_3$ substrates



$$\omega_0 = 1/\sqrt{LC} \sim 1/n$$

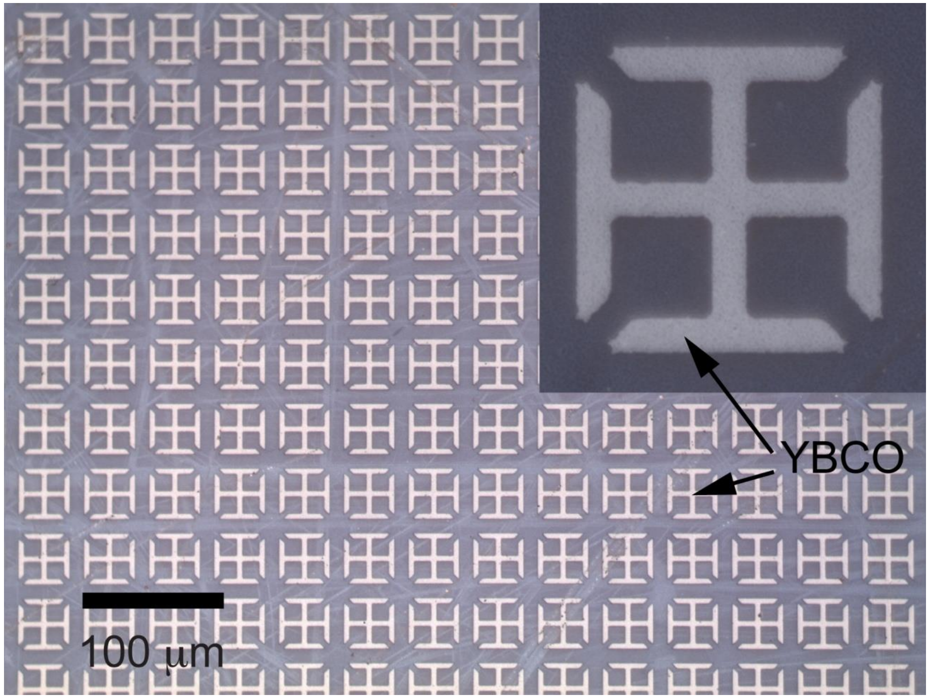


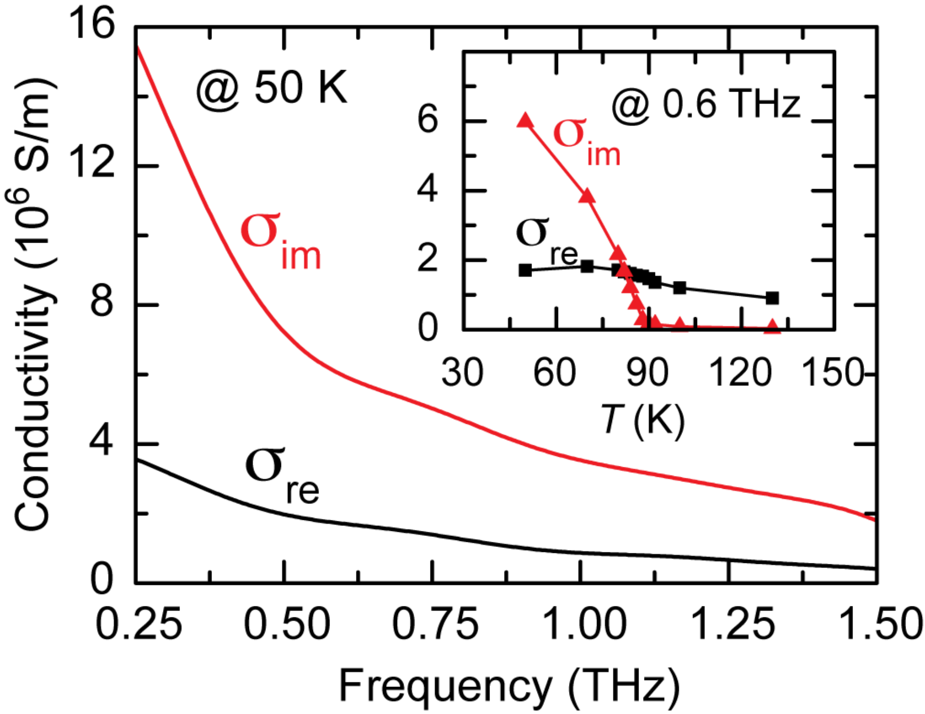


Singh *et al.*, *Opt. Lett.* **36,** 1230 (2011).

Superconducting THz MMs enable thermal tunability

High quality epitaxial YBCO film on LAO by Pulsed Laser Deposition with *Tc* ~ 90 K and thickness 180 nm

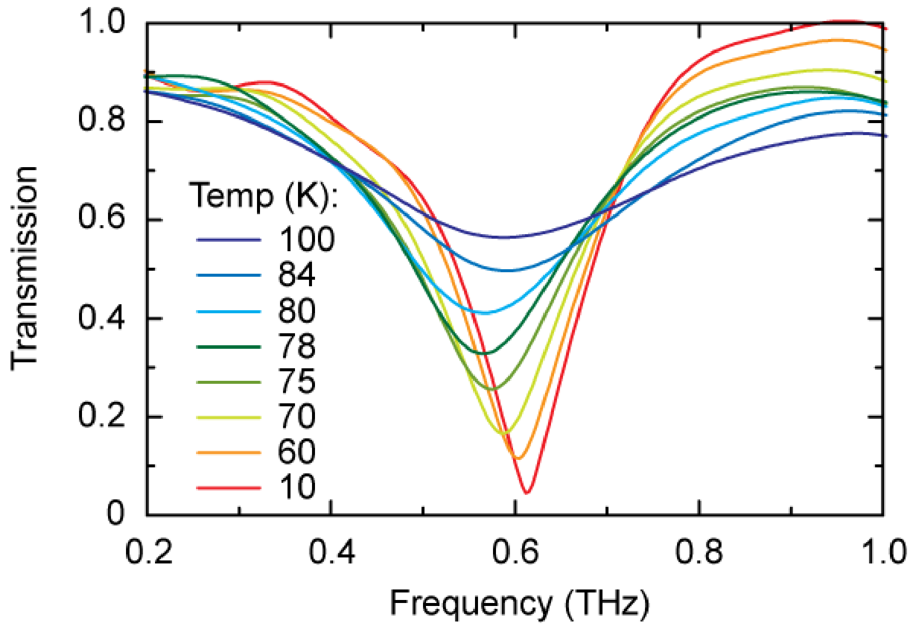




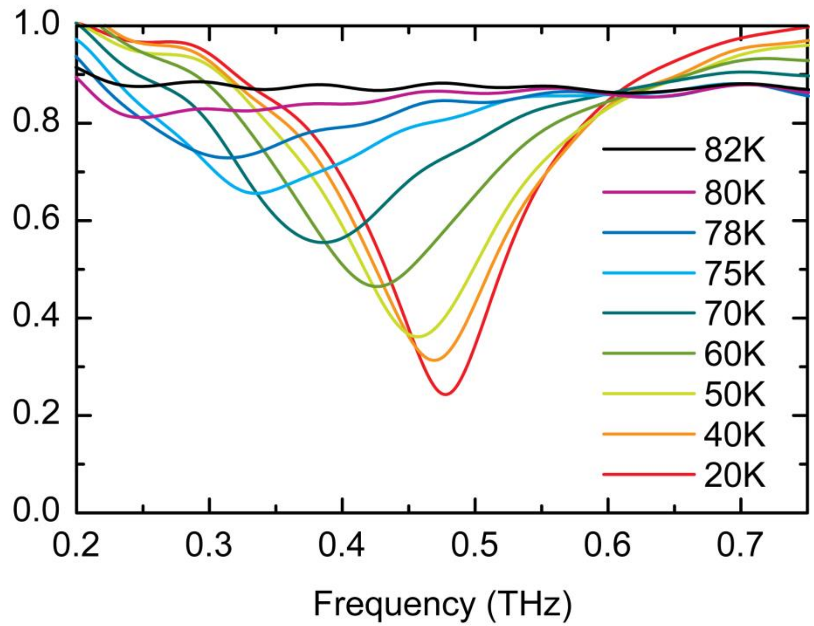
Experimentally measured complex conductivity of YBCO

Thermally Tunable Metamaterial Resonance

180 nm thick YBCO MM

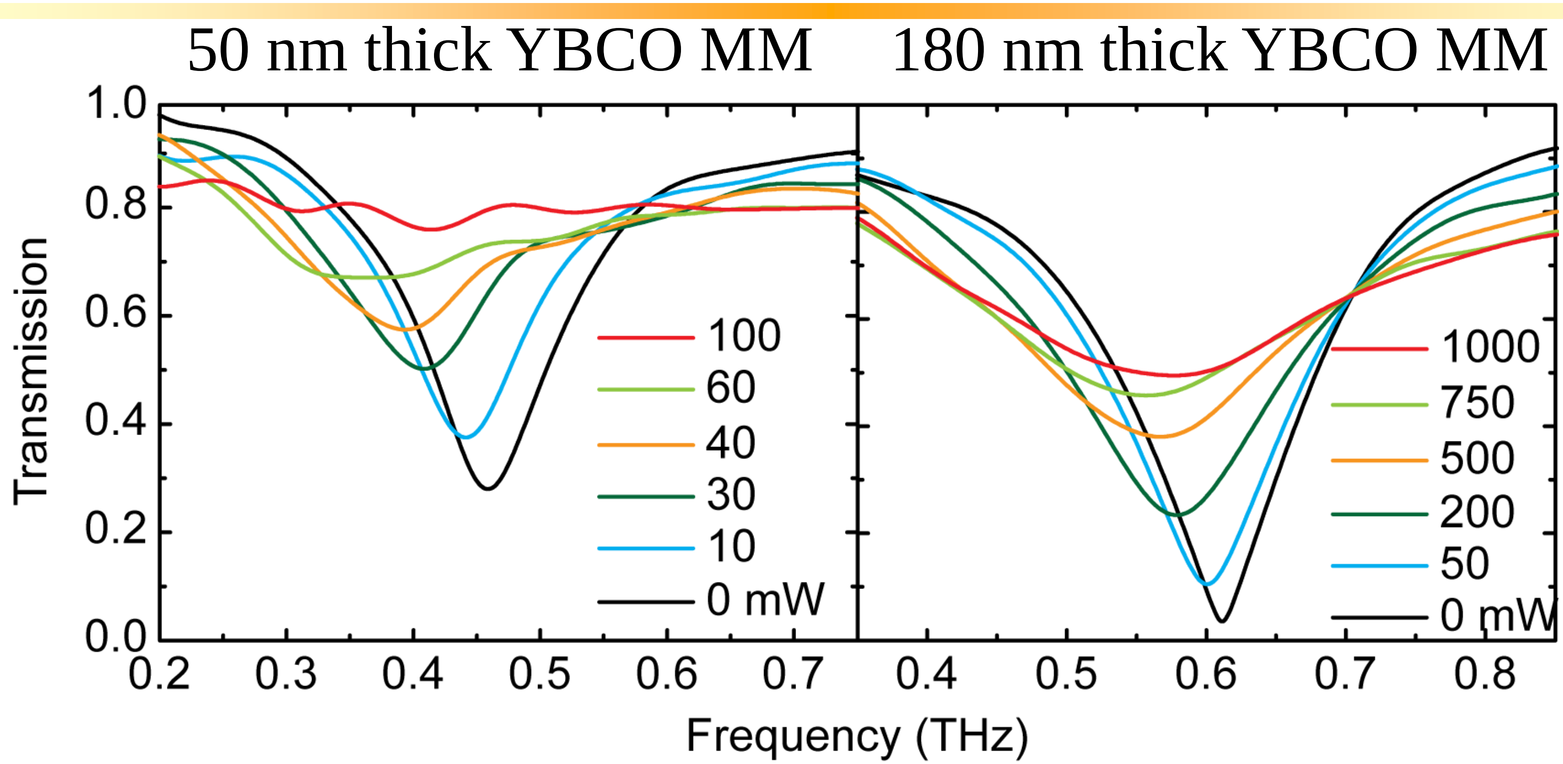


50 nm thick YBCO MM



- Switching resonance strength and shifting resonance frequency
- Decreasing the thickness results in:
  - A red-shift of the resonance frequency
  - A larger tuning range and higher tuning efficiency

MM resonance tuning by photoexcitation

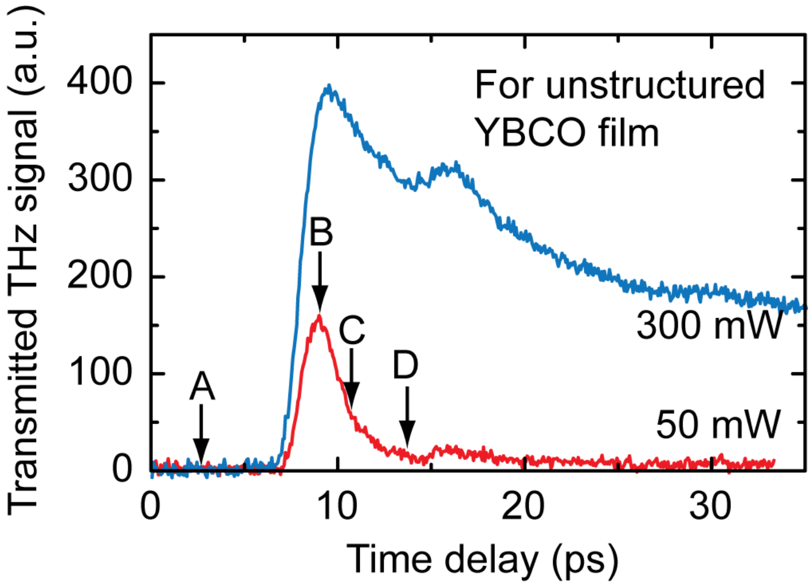


Metamaterials made from different thicknesses of YBCO films

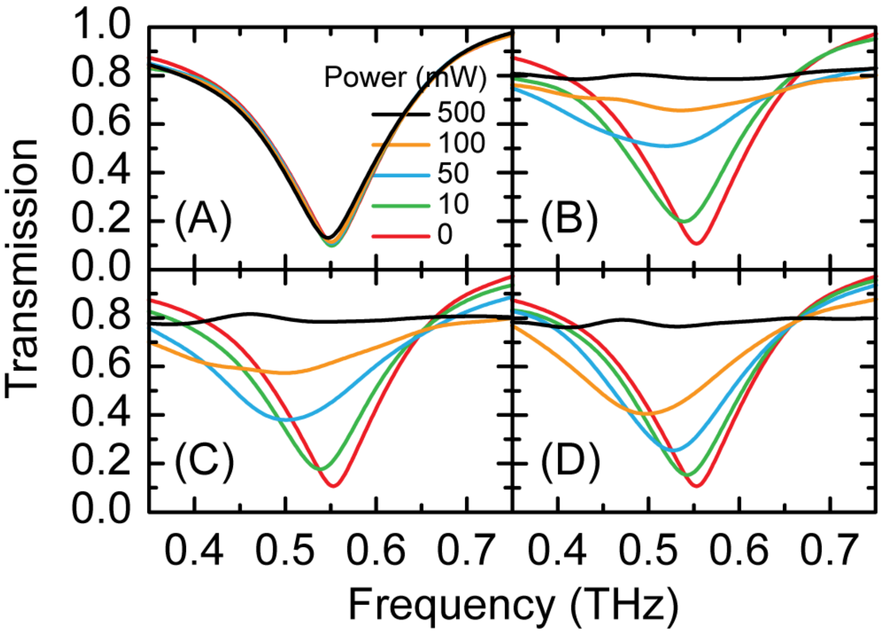
- Resonance tuning by photoexcitation depends on thickness

Ultrafast Dynamics

Optical Pump THz Probe



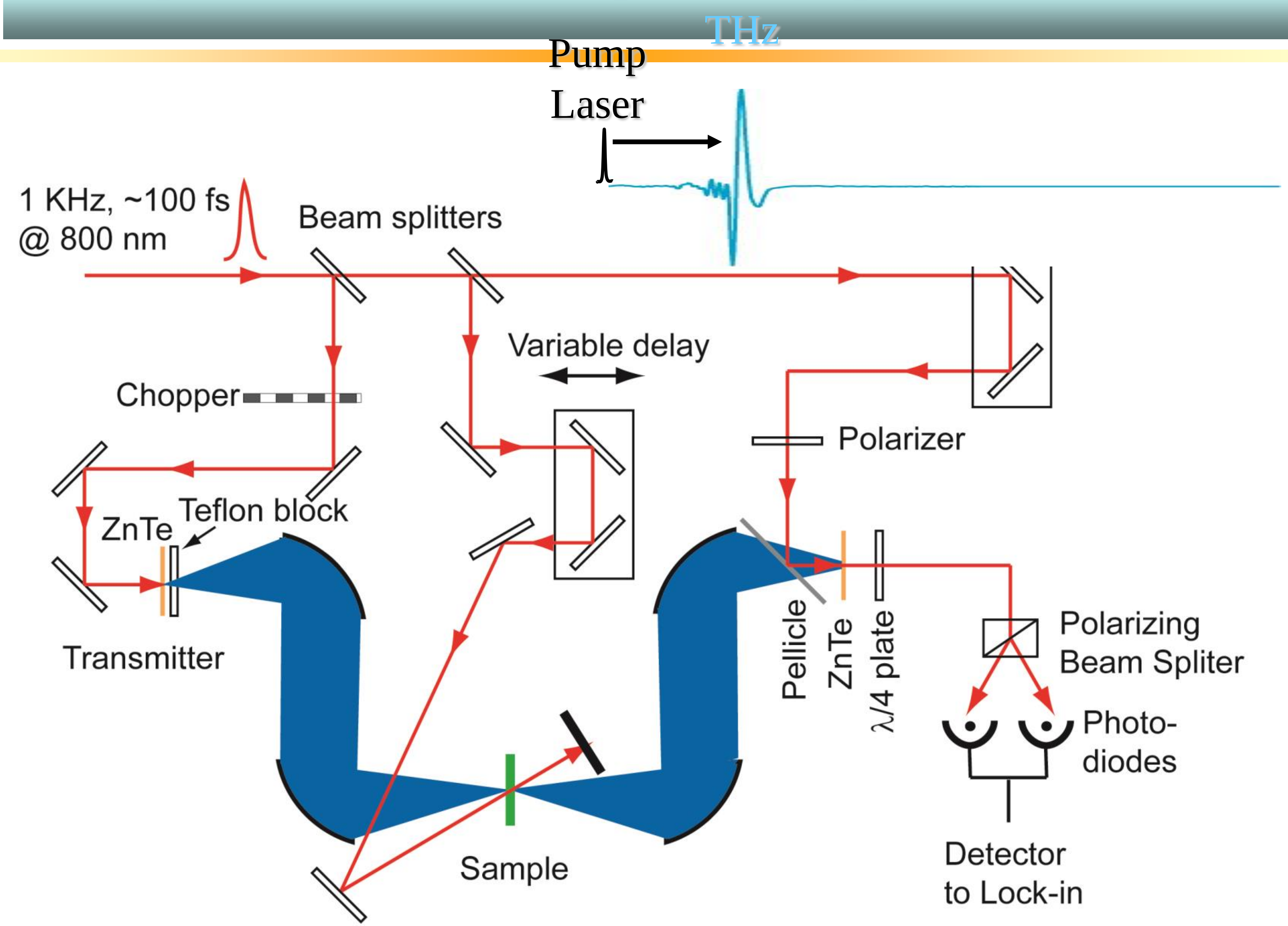
At various pump-probe delays



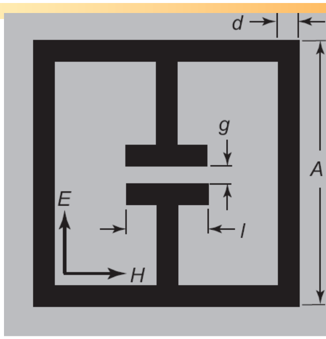
- Relaxation (recombination) time is a few ps
- Increasing the pump power results in a long relaxation tail due to thermal effects

Singh *et al.*, *Nanophotonics*, (2012), in press

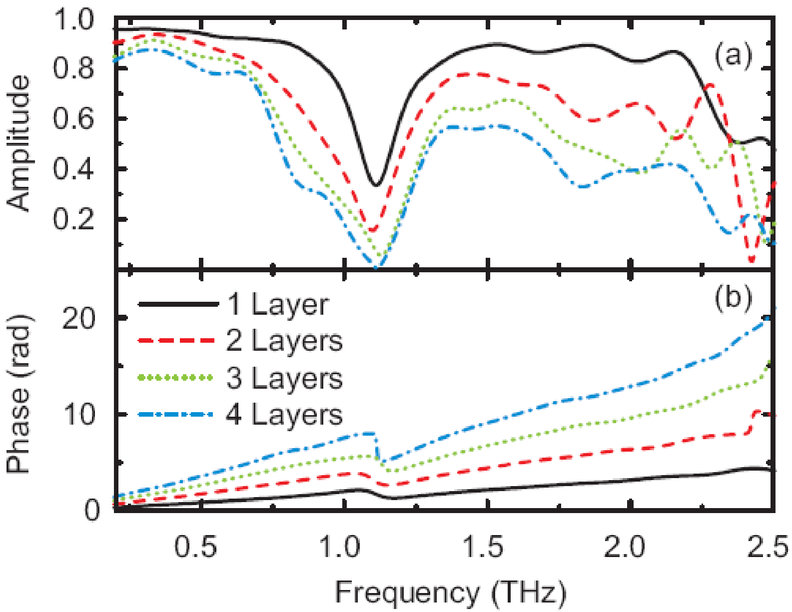
Optical THz Switch: Optical-Pump Terahertz-Probe



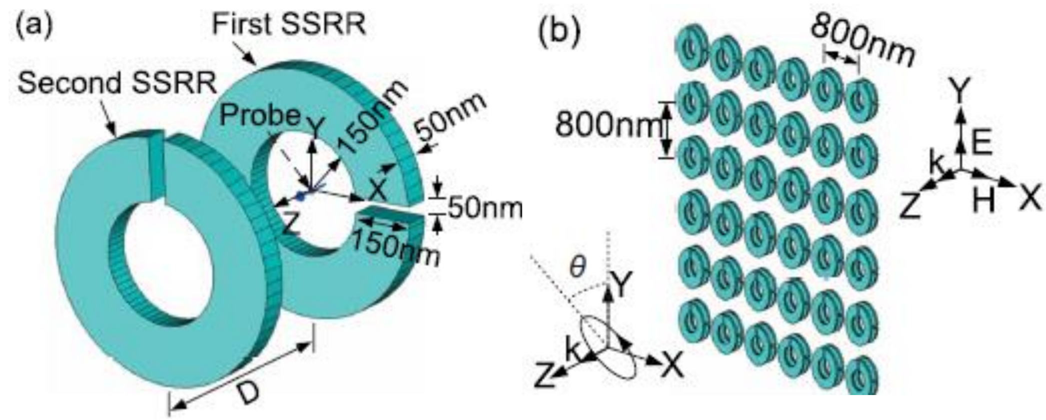
Interaction Between Layers



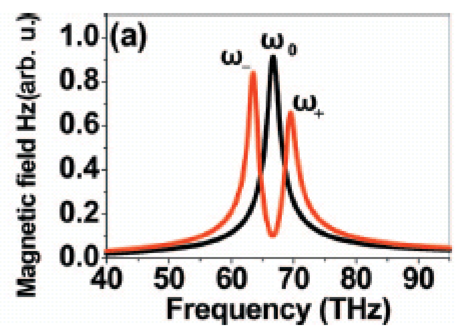
$d \sim \lambda_{res}/5$

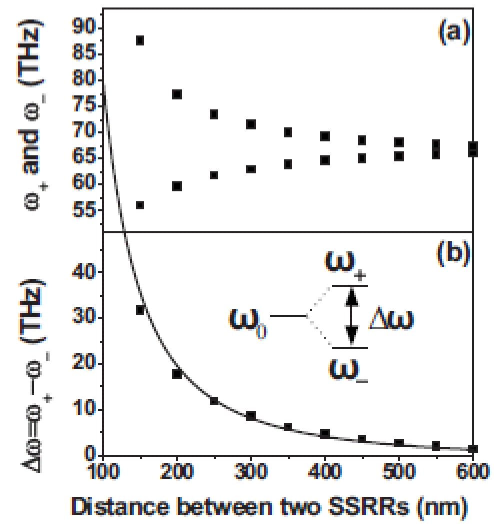


*A. Azad, et. al Terahertz Science and Technology, **94**, 15 (2009)*



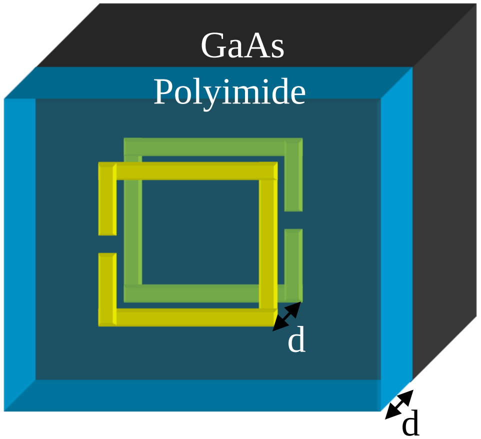
$d \sim \lambda_{res}/50$



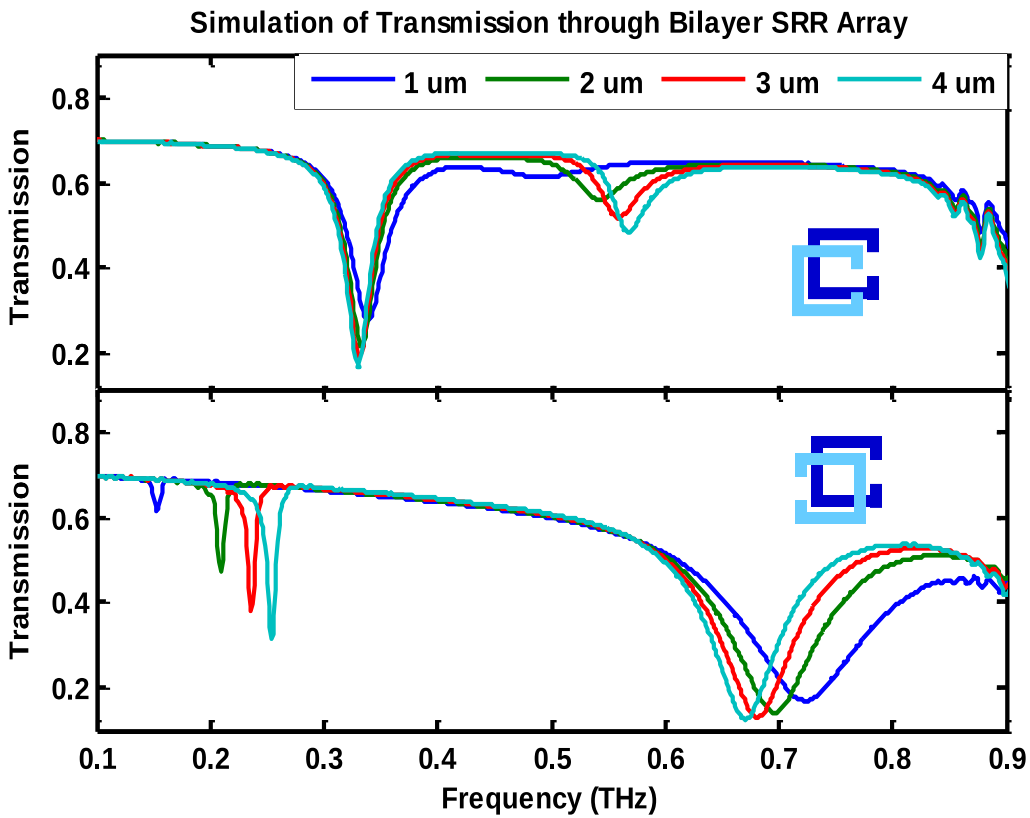


*H. Liu, et. al Phys. Rev. **76**, 073101 (2007)*

Coupled SRRs (Bi-Layer)

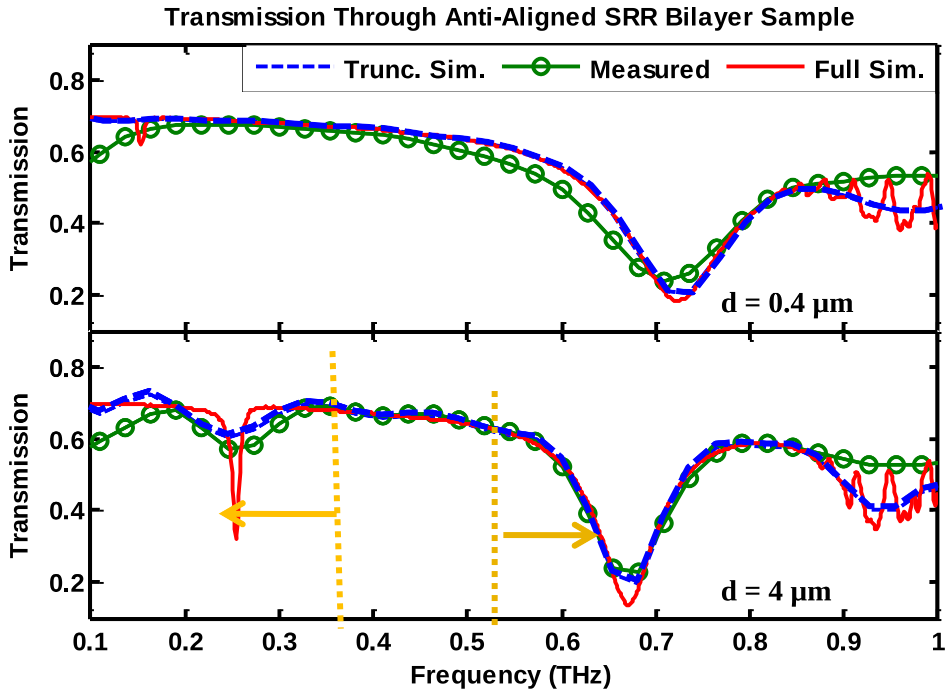


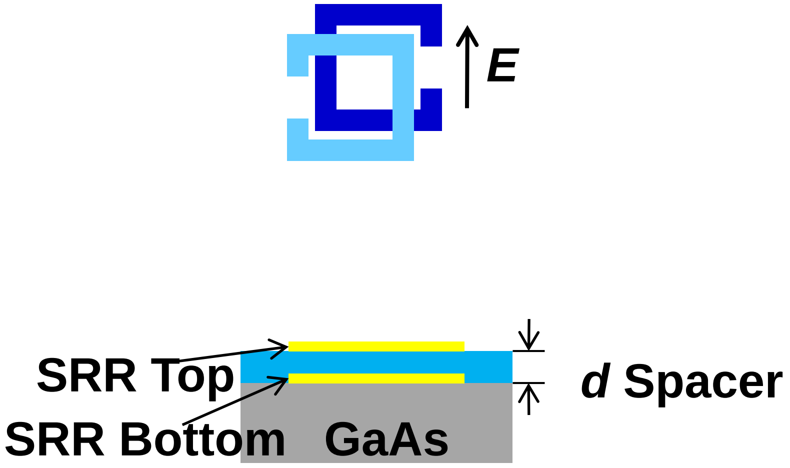
***d* ~ λ_{res}/500**



M. T. Reiten, et. al, App. Phys. Lett. ***98*** *131105 (2011)*

Simulation. vs. Measurement for Anti-Aligned SRR

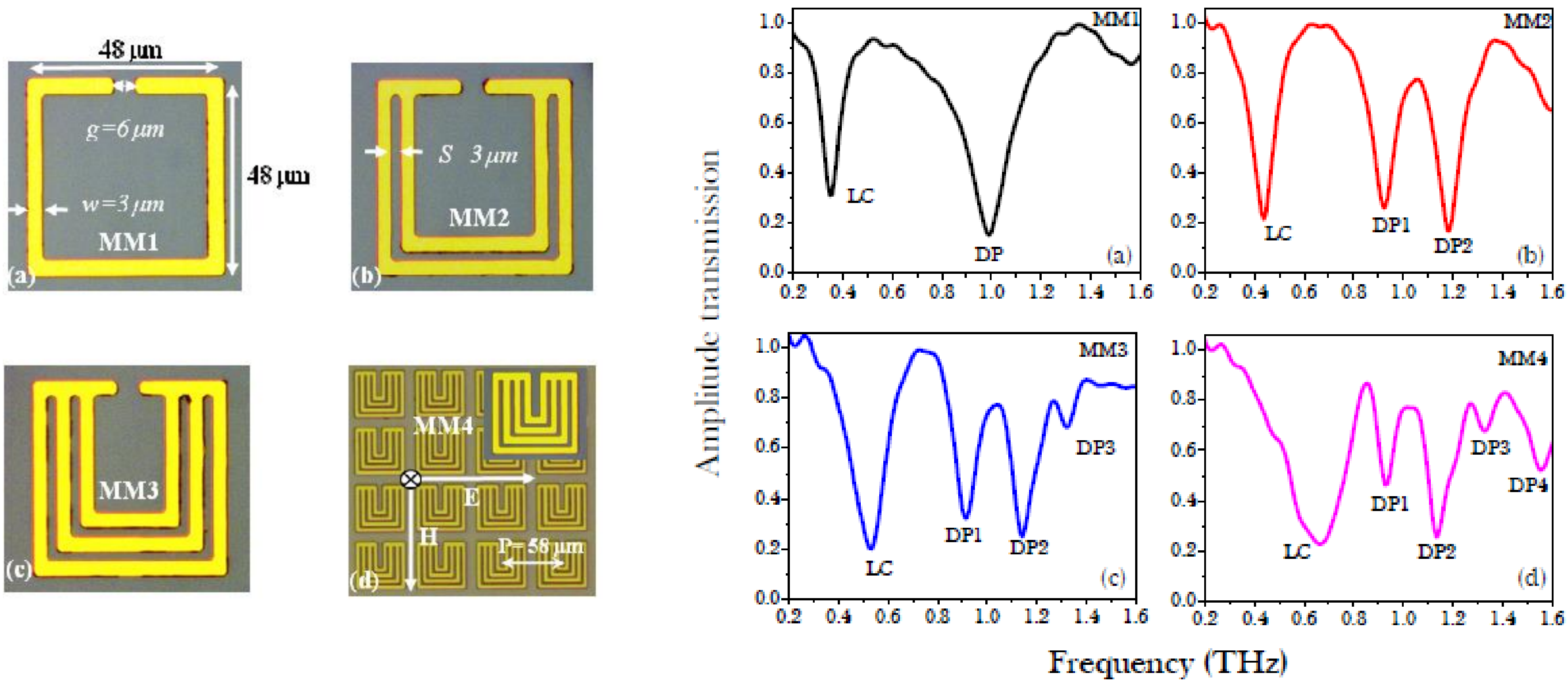




SRR Top Only 0.53 THz

SRR Bottom Only 0.34 THz

Broadband Metamaterial



D. R. Chowdhury et al., Optics Express 19, 15821 (2011)

Broadband Metamaterial